TC 9-60

COMMUNICATIONS-ELECTRONICS FUNDAMENTALS

Basic Principles of Alternating Current and Direct Current

AUGUST 2004

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Communications-Electronics Fundamentals

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Contents

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Preface

This publication is a reference TC for the electronics-engineering field. It provides information for the 35-series MOSs.

This publication provides background knowledge for the electronics technician. The technician is required to safely and efficiently operate and maintain electrical systems and apparatus. This TC reinforces good electrical practices and promotes the safe operation of the many electrical systems in the electronic shop.

This publication covers the basics of direct current and alternating current. It introduces the physical properties of electricity and electromagnetism and describes how electricity is produced, stored, distributed, and used. This publication also identifies important safety practices to follow when working with electricity.

The proponent of this publication is Headquarters, United States Army Training and Doctrine Command (HQ USATRADOC). Send comments and recommendations for improving this publication on DA Form 2028 (Recommended Changes to Publications and Blank Forms) directly to: Commander, USACASCOM&FL, Training Directorate, Ordnance Training Division, ATTN: ATCL-AO, 401 First Street, Fort Lee, Virginia 23801-1511.

Unless this publication states otherwise, masculine nouns and pronouns do not refer exclusively to men.

Chapter 1

Safety

Completing everyday work activities successfully means performing them safely. How you prepare and conduct your work activities reflects on your job performance. In no other field is attention to safety more important than in the electrical field. This chapter reviews the safety practices you should follow when working with electrical equipment.

OVERVIEW

1-1. Current is the measure of shock intensity. The passage of even a very small current through a vital part of the human body can kill. At about 100 milliamperes (0.1 ampere), the shock is fatal if it lasts for one second or more. Fatalities have resulted from voltages as low as 30 volts.

1-2. Wet conditions add to the chance of receiving an electrical shock. When a person's body is likely to be in contact with a metal structure, the body's resistance may be low because of perspiration or damp clothing. Personnel must be aware that electrical shock hazards exist.

1-3. Accidentally placing or dropping a metal tool, ruler, flashlight case, or other conducting articles across an energized terminal can cause a short circuit. The resulting arc and fire, even on a relatively low-voltage circuit, may extensively damage equipment and seriously injure personnel. Touching one conductor of an ungrounded electrical system while the body is in contact with a metal surface can be fatal.

WARNING

Treat all energized electrical circuits as potential hazards at ALL times.

DANGER SIGNS OF EQUIPMENT MALFUNCTION

1-4. Be constantly alert for any signs that might indicate a malfunction of electrical equipment. When danger signals are noted, report them immediately to the NCOIC or the OIC. The following are examples of danger signals:

- Fire, smoke, sparks, arcing, or an unusual sound from an electric motor.
- Frayed and damaged cords or plugs.
- Receptacles, plugs, and cords that feel warm to the touch.
- Slight shocks felt when handling electrical equipment.
- Unusually hot running electric motors and other electrical equipment.

- An odor of burning or overheated insulation.
- Electrical equipment that either fails to operate or operates irregularly.
- Electrical equipment that produces excessive vibrations.

CAUTION

Do not operate faulty equipment. Stand clear of any suspected hazard and instruct others to do likewise.

ELECTRICAL SHOCK

1-5. Electrical shock is a jarring, shaking sensation. Usually it feels like receiving a sudden blow. If the voltage and current are sufficiently high, unconsciousness occurs. Electrical shock may severely burn the skin. Muscular spasms may cause the hands to clasp the apparatus or wire, making it impossible to let go.

RESCUE AND CARE OF SHOCK VICTIMS

1-6. See FM 4-25.11 for complete coverage of CPR and treatment of burn and shock victims. The following procedures are recommended for the rescue and care of victims of electrical shock:

- Remove the victim from electrical contact at once, but do not endanger yourself. Touching a shock victim who is still in contact with the energized circuit will make you another shock victim. Help the shock victim by de-energizing the affected circuit. Use a dry stick, rope, belt, coat, blanket, shirt, or any other nonconductor of electricity to drag or push the victim to safety.
- Determine the cardiopulmonary status of the victim. Start CPR if spontaneous respiration or circulation is absent.
- Once the person is stabilized, attend to all physical injuries, as they would normally be treated. If there are no chest or head injuries, lay the victim face up in a prone position with the feet about 12 inches higher than the head. If the victim has chest or head injuries, elevate the head slightly. If there is vomiting or if there are facial injuries that are causing bleeding into the throat, place the victim on his stomach with his head turned to one side. The head should be 6 to 12 inches lower than the feet.
- Keep the victim warm. The injured person's body heat must be conserved. Cover the victim with one or more blankets, depending on the weather and the person's exposure to the elements. Avoid artificial means of warming (such as hot water bottles).

- Do not give drugs, food, or liquids if medical attention will be available within a short time. If necessary, liquids may be administered. Use small amounts of water, tea, or coffee. Never give alcohol, opiates, or other depressant substances.
- Send for medical personnel (a doctor, if available) at once. Do not under any circumstances leave the victim until medical help arrives.

SAFETY PRECAUTIONS TO PREVENT ELECTRICAL SHOCK

1-7. Observe the following safety precautions when working on electrical equipment:

- When work must be done in the immediate vicinity of electrical equipment, check with the NCOIC responsible for maintaining the equipment to avoid any potential hazards. Stand clear of operating radar and navigational equipment.
- Never work alone. Another person could save your life if you receive an electrical shock.
- Work on energized circuits only when absolutely necessary. The power source should be tagged out at the nearest source of electricity for the component being serviced.
- Keep the covers of all fuse boxes, junction boxes, switch boxes, and wiring accessories closed. Report any cover that is not closed or that is missing to the NCOIC responsible for its maintenance. Failure to do so may result in injury to personnel or damage to equipment if an accidental contact is made with exposed live circuits.
- Discharge capacitors before working on de-energized equipment. Take special care to discharge capacitors properly. Injuries to personnel or damage to equipment could result if improper procedures are used.
- When working on energized equipment, stand on a rubber mat to insulate yourself from the steel deck.
- When working on an energized circuit, wear approved electrical insulating rubber gloves (the rubber gloves used with NBC suits are not acceptable). Cover as much of your body as practical with an insulating material (such as shirtsleeves). This is especially important when working in a warm space where you may perspire.
- If possible, de-energize equipment before hooking up or removing test equipment.
- When working on energized electrical equipment, work with only one hand inside the equipment. Keep the other hand clear of all conductive materials that may provide a path for current flow.

- Wear safety goggles. Sparks could damage your eyes. The sulfuric acid contained in batteries and the oils in electrical components can cause blindness.
- Ensure that all tools are adequately insulated when working on energized electrical equipment.
- Never work on electrical equipment while wearing rings, watches, identification tags, or other jewelry.
- Never work on electrical equipment while wearing loose-fitting clothing. Be careful of loose sleeves and the BDU shirttails.
- Ensure that there are protective guards on all rotating and reciprocating parts of the electric motors.
- Remain calm and consider the possible consequences before performing any action.

WARNING

To avoid injury and to prevent damage to equipment, keep liquids away from electrical equipment.

1-8. Carbon dioxide is the choice for fighting electrical fires. It has a nonconductive extinguishing agent and does not damage equipment. However, the ice that forms on the horn of the extinguisher will conduct electricity.

SAFETY

Questions

1. What is the measure of shock intensity?
2. What can happen if conducting articles are placed or dropped across an energized terminal?
3. To whom should you report danger signals?
4. What FM covers CPR and treatment of burn and shock victims?
5. What should you never give a shock victim?
6. What should you stand on when working on energized equipment?
7. In what position should you place a victim that is vomiting or has facial injuries that is causing bleeding in the throat?
8. What is the best substance to use to fight electrical fires?

Chapter 2

Fundamentals of Electricity

Electricity is a fundamental entity of nature that results from the interaction of positively and negatively charged particles of matter. This chapter describes the atom and the particles that make up the atom. It reviews the forces that direct the interaction of these charged particles to produce magnetic and electric effects. It shows how these interactions result in electrical energy. This chapter also describes the fundamentals of magnetism, which are also covered in greater depth in Chapter 5.

MATTER

2-1. Matter is anything that occupies space. Examples of matter are air, water, automobiles, clothing, and even our own bodies. Matter can be found in any one of three states: solid, liquid, and gas.

2-2. Subatomic particles are the building blocks of all matter. Even though the usual mechanical tools cannot measure these particles, they are nonetheless matter. Over 99 percent of the matter in the universe is subatomic material called plasma. Plasma exists throughout the universe as interstellar gases and stars. Plasma is a kind of "subatomic particle soup." Plasma exists on earth only in small quantities. It is seen in the form of the Aurora Borealis, inside neon lamps, in lightning bolts, and in electricity. Plasma is a collection of positive and negative charges, about equal in number or density and forming a neutral charge (distribution) of matter. Plasma is considered the fourth state of matter.

ELEMENTS, COMPOUNDS, AND MIXTURES

2-3. An element is a substance that cannot be reduced to a simpler substance by chemical means. It is composed of only one type of atom. More than 100 elements are known. Some examples are iron, gold, silver, copper, and oxygen. All substances are composed of one or more of these elements.

2-4. When two or more elements are chemically combined, the resulting substance is a compound. A compound is a chemical combination of elements that can be separated by chemical means but not by physical means. Examples of common compounds are water (hydrogen and oxygen) and table salt (sodium and chlorine).

2-5. A mixture is a combination of elements and/or compounds (not chemically combined) that can be separated by physical means. Examples of mixtures are air (which is made up of nitrogen, oxygen, carbon dioxide, and small amounts of several rare gases) and seawater (which consists chiefly of salts and water).

ATOMS AND MOLECULES

2-6. An atom is the smallest particle of an element that retains the characteristics of that element. The atoms of one element differ from the atoms of all other elements. Since more than 100 elements are known, it follows that there must be more than 100 different atoms, or a different atom for each element. Just as combining the proper letters of the alphabet can make thousands of words, so thousands of different materials can be made by chemically combining the proper atoms.

2-7. Any particle that is a chemical combination of two or more atoms is a molecule. In a compound, the molecule is the smallest particle that has all the characteristics of that compound. For example, water is a compound made up of two atoms of hydrogen and one atom of oxygen. It may be chemically or electrically divided into its separate atoms, but it cannot be divided by physical means.

2-8. The electrons, protons, and neutrons of one element are identical to those of any other element. However, the number and arrangement of electrons and protons within the atom are different for each element.

2-9. The electron is a small negative charge of electricity. The proton has a positive charge equal and opposite to the electron. Scientists have measured the mass and size of the electron and proton and found the mass of the proton is approximately 1,837 times that of the electron. In the nucleus is a neutral particle called the neutron. A neutron has a mass approximately equal to that of a proton, but with no electrical charge. According to a popular theory, the electrons, protons, and neutrons of the atoms are arranged like a miniature solar system. The protons and neutrons form the heavy nucleus with a positive charge around which the very light electrons revolve.

2-10. Figure 2-1 shows a theoretical representation of one hydrogen atom and one helium atom. Each has a relatively simple structure. The hydrogen atom has only one proton in the nucleus with one electron rotating around it. The helium atom has a nucleus made up of two protons and two neutrons, with two electrons rotating outside the nucleus. Elements are classified numerically according to the complexity of their atoms. The number of protons in the atom's nucleus determines its atomic number.

2-11. Individually, an atom contains an equal number of protons and electrons. An atom of hydrogen, which contains one proton and one electron, has an atomic number of 1. Helium, with two protons and two electrons, has an atomic number of 2. The complexity of atomic structure increases with the number of protons and electrons.

ENERGY LEVELS

2-12. Since an electron in an atom has both mass and motion, it contains two types of energy. By virtue of its motion, the electron contains kinetic energy. Due to its position, it also contains potential energy. The total energy contained by an electron (kinetic plus potential) is the factor that determines the radius of the electron orbit. To keep this orbit, an electron must neither gain nor lose energy.

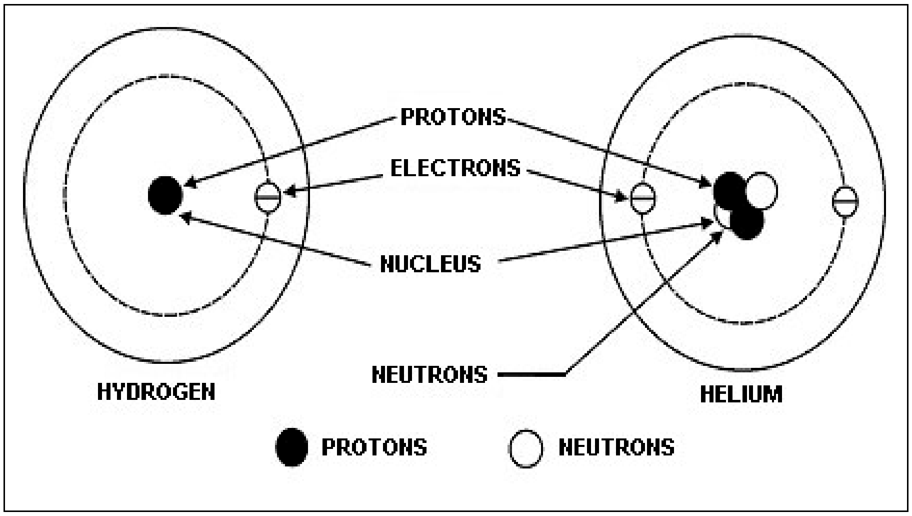

Figure 2-1. Structures of Simple Atoms

2-13. Light is a form of energy. However, the physical form in which this energy exists is not known. One accepted theory proposes the existence of light as tiny packets of energy called photons. Photons can contain various quantities of energy. The amount depends upon the color of the light involved. If a photon of sufficient energy collides with an orbital electron, the electron absorbs the photon's energy (see Figure 2-2). The electron, which now has a greater than normal amount of energy, will jump to a new orbit farther from the nucleus. The first new orbit to which the electron can jump has a radius four times the radius of the original orbit. Had the electron received a greater amount of energy, the next possible orbit to which it could jump would have a radius nine times the original. Therefore, each orbit represents one of a large number of energy levels that the electron may attain. However, the electron cannot jump to just any orbit. The electron will remain in its lowest orbit until a sufficient amount of energy is available, at which time the electron will accept the energy and jump to one of a series of permissible orbits. An electron cannot exist in the space between energy levels. This indicates that the electron will not accept a photon of energy unless it contains enough energy to elevate itself to one of the higher energy levels. Heat energy and collisions with other particles can also cause the electron to jump orbits.

2-14. Once the electron is elevated to an energy level higher than the lowest possible energy level, the atom is in an excited state. The electron remains in this excited condition for only a fraction of a second before it radiates the excess energy and returns to a lower energy orbit.

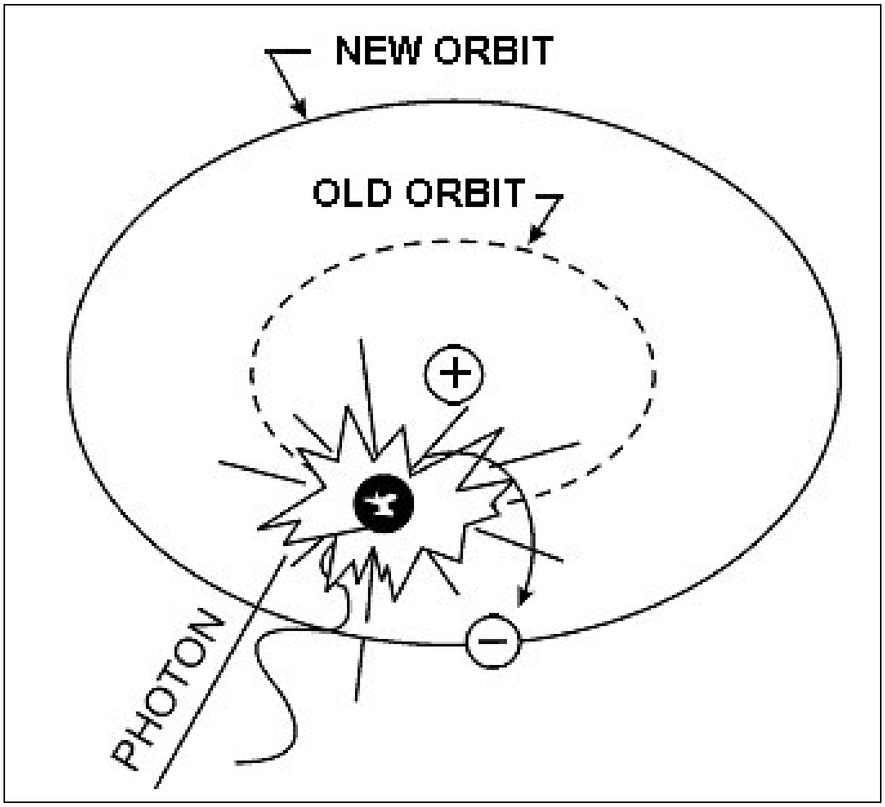

Figure 2-2. Excitation by a Photon

2-15. To illustrate this principle, assume that a normal electron has just received a photon of energy sufficient to raise it from the first to the third energy level. In a short period of time, the electron may jump back to the first level and emit a new photon identical to the one it received. Another alternative would be for the electron to return to the lower level in two jumps: from the third to the second and then from the second to the first. In this case, the electron would emit two photons, one for each jump. Each of these photons would have less energy than the original photon that excited the electron.

2-16. This principle is used in the fluorescent light where ultraviolet light photons, invisible to the human eye, bombard a phosphor coating on the inside of a glass tube. When the phosphor electrons return to their normal orbits, they emit photons of light that are visible. By using the proper chemicals for the phosphor coating, any color of light, including white, may be obtained.

2-17. These basic principles apply equally to the atoms of more complex elements. In atoms containing two or more electrons, the electrons interact with each other and the exact path of any one electron is very difficult to predict. However, each electron lies in a specific energy band and the orbits are considered as an average of the electron's position.

SHELLS AND SUBSHELLS

2-18. The difference between the chemical activity and stability of atoms depends on the number and position of the electrons within the atom. In general, the electrons reside in groups of orbits called shells. These shells are elliptically shaped and are assumed to be located at fixed intervals. Therefore, the shells are arranged in steps that correspond to freed energy levels. The shells and the number of electrons required to fill them may be predicted by the employment of Pauli's exclusion principle. This principle specifies that each shell will contain a maximum of 2n squared electrons, where n corresponds to the shell number starting with the one closest to the nucleus. By this principle the second shell, for example, would contain $2(2^2)$ or 8 electrons when full.

SHELL DESIGNATIONS

2-19. In addition to being numbered, the shells are given letter designations (see Figure 2-3). Starting with the shell closest to the nucleus and progressing outward, the shells are labeled K, L, M, N, O, P, and Q, respectively. The shells are considered full or complete when they contain the following quantities of electrons: 2 in the K shell, 8 in the L shell, 18 in the M shell, and so forth. Each of these shells is a major shell and can be divided into four subshells (labeled s, p, d, and f). Like the major shells, the subshells are limited as to the number of electrons they can contain. Therefore, the "s" subshell is complete when it contains 2 electrons, the "p" subshell when it contains 6, the "d" subshell when it contains 10, and the "f" subshell when it contains 14 electrons.

2-20. Since the K shell can contain no more than two electrons, it must have only one subshell, the s subshell. The M shell has three subshells: s, p, and d. Adding together the electrons in the s, p, and d subshells equals 18, the exact number required to fill the M shell. Figure 2-4 shows the electron configuration for copper. The copper atom contains 29 electrons, which completely fill the first three shells and subshells, leaving one electron in the "s" subshell of the N shell.

VALENCE

2-21. The outermost shell of the atom is called the valence shell. The number of electrons present in this shell determines the atom's ability to gain or lose an electron, which in turn determines the chemical boding and electrical properties of the atom. An atom lacking only one or two electrons from its outer shell will easily gain electrons to complete its shell. However, a large amount of energy is required to free any of its electrons. An atom with a relatively small number of electrons in its shell compared to the number of electrons required to fill the shell will easily lose these valence electrons.

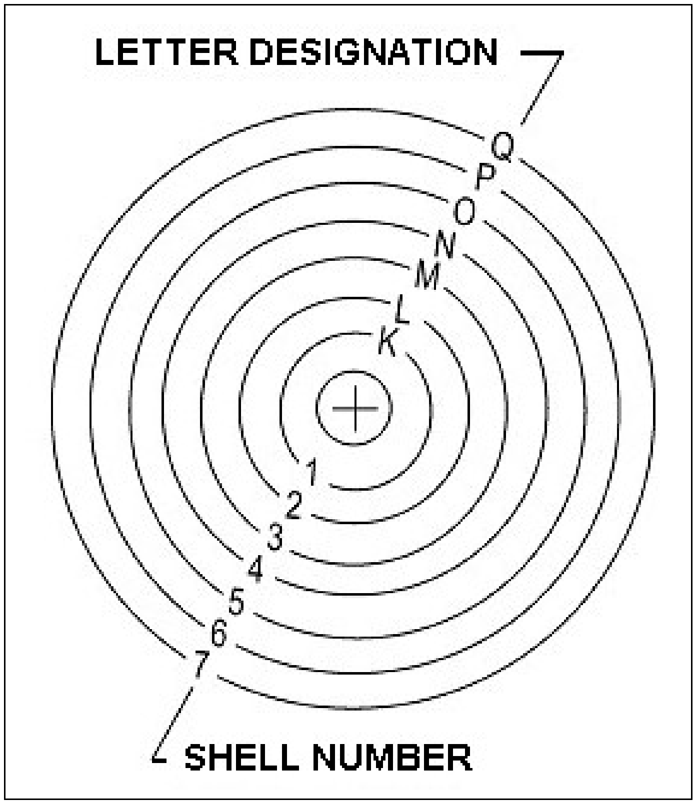

Figure 2-3. Shell Designation

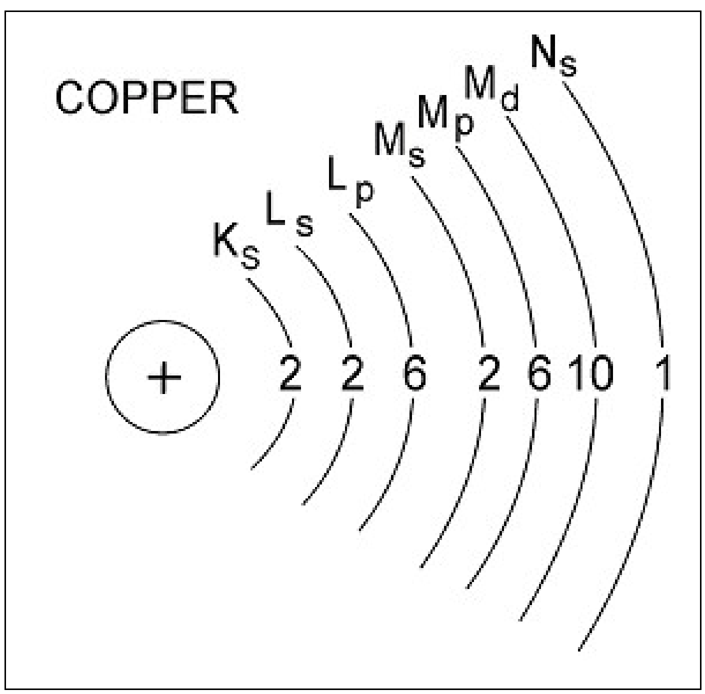

Figure 2-4. Copper Atom

IONIZATION

2-22. For an atom to lose or gain an electron, it must be ionized. For ionization to take place, a transfer of energy must change the internal energy of the atom. An atom with more than its normal amount of electrons acquires a negative charge and is called a negative ion. The atom that gives up some of its normal electrons is left with fewer negative charges than positive charges and is called a positive ion. Therefore, ionization is the process by which an atom loses or gains electrons.

CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

2-23. Since every electrical device is constructed of parts made from ordinary matter, the effects of electricity on matter must be well understood. Depending on their ability to conduct an electric current, all elements of matter fit into one of three categories: conductors, semiconductors, and insulators. Conductors are elements that transfer electrons very readily. Insulators have an extremely high resistance to the flow of electrons. All material between these two extremes is referred to as a semiconductor.

2-24. The electron theory states that all matter is composed of atoms and the atoms are composed of smaller particles called protons, electrons, and neutrons. The electrons orbit the nucleus, which contains the protons and neutrons. Electricity is most concerned with the valence electrons. These electrons break loose from their parent atom the easiest. Normally, conductors have no more than three valence electrons; insulators have five or more; and semiconductors have four.

2-25. The electrical conductivity of matter depends on the atomic structure of the material from which the conductor is made. In any solid material (such as copper) the atoms that make up the molecular structure are bound firmly together. At room temperature, copper contains a large amount of heat energy. Since heat energy is one method of removing electrons from their orbits, copper contains many free electrons that can move from atom to atom. When not under the influence of an external force, these electrons move in a haphazard manner within the conductor. This movement is equal in all directions so that electrons are not lost or gained by any part of the conductor. When controlled by an external force, the electrons move generally in the same direction. The effect of this movement is felt almost instantly from one end of the conductor to the other. This electron movement is called an electric current.

2-26. Some metals are better conductors of electricity than others. Silver, copper, gold, and aluminum exchange valence electrons readily and make good conductors. Silver is the best conductor, followed by copper, gold, and aluminum. Copper is used more often than silver because of cost. Aluminum is used where weight is a major consideration, such as in high-tension power lines with long spans between supports. Gold is used where oxidation or corrosion is a consideration and good conductivity is required. The ability of a conductor to handle current also depends on its physical dimensions. Conductors are usually found in the form of wire, but may be bars, tubes, or sheets.

2-27. Nonconductors fail to exchange valence electrons because their outer shells are completed with tightly bound valence electrons of their own. These materials are called insulators. Some examples of these materials are rubber, plastic, enamel, glass, dry wood, and mica. Just as there is no perfect conductor, neither is there a perfect insulator.

2-28. Some materials are neither good conductors nor good insulators because their electrical characteristics fall between those of conductors and insulators. These in-between materials are semiconductors. Germanium and silicon are two common semiconductors used in solid-state devices.

ELECTROSTATICS

2-29. Electrostatics is electricity at rest. An example of an effect of electrostatics is the way a person's hair stands on end after a vigorous rubbing. Knowledge of electrostatics provides the underlying concepts needed to understand electricity and electronics.

2-30. When an amber rod is rubbed with fur, the rod attracts some very light objects such as bits of paper and shavings of wood. Other substances possess qualities of attraction similar to amber. Among these are glass (when rubbed with silk) and ebonite (when rubbed with fur). All the substances with properties similar to those of amber are called *electrics*, a word of Greek origin meaning amber. A substance such as amber or glass when given a vigorous rubbing is electrified or charged with electricity.

2-31. When a glass rod is rubbed with fur, both the glass rod and the fur become electrified. Certain substances attracted to the glass rod are repelled by the fur and vice versa. There are two opposite kinds of electrical charge: positive and negative. The charge produced on a glass rod when it is rubbed with silk is positive. The charge produced on the silk is negative. Those bodies that are not electrified or charged are neutral.

STATIC ELECTRICITY

2-32. In a natural or neutral state, each atom in a body of matter has the proper number of electrons in orbit around it. Therefore, the whole body of matter composed of the neutral atoms is also electrically neutral. In this state, it has zero net charge. Electrons will neither leave nor enter the neutrally charged body if it comes in contact with other neutral bodies. However, if any electrons are removed from the atoms of a body of matter, more protons than electrons will remain and the whole body of matter will become electrically positive. If the positively charged body comes in contact with a body having a normal charge or a negative (too many electrons) charge, an electric current will flow between them. Electrons will leave the more negative body and enter the positive body. This electron flow will continue until both bodies have equal charges. When two bodies of matter with unequal charges are near one another, an electric force is exerted between them. However, because they are not in contact, their charges cannot equalize. Such an electric force, where current cannot flow, is called static electricity (static in this instance means not moving). It is also referred to as an electrostatic force.

2-33. One of the easiest ways to create a static charge is by friction. When two pieces of matter are rubbed together, electrons can be wiped off one material onto the other. If both materials are good conductors, it is hard to obtain a detectable charge on either because equalizing currents can flow easily between the conducting materials. These currents equalize the charges almost as fast as they are created. A static charge is more easily created between nonconducting materials. When a hard rubber rod is rubbed with fur, the rod will accumulate electrons given up by the fur (see Figure 2-5, views A and B). Since both materials are poor conductors, very little equalizing current can flow and an electrostatic charge builds up. When the charge becomes great enough, current will flow regardless of the poor conductivity of the materials. These currents cause visible sparks and produce a crackling sound.

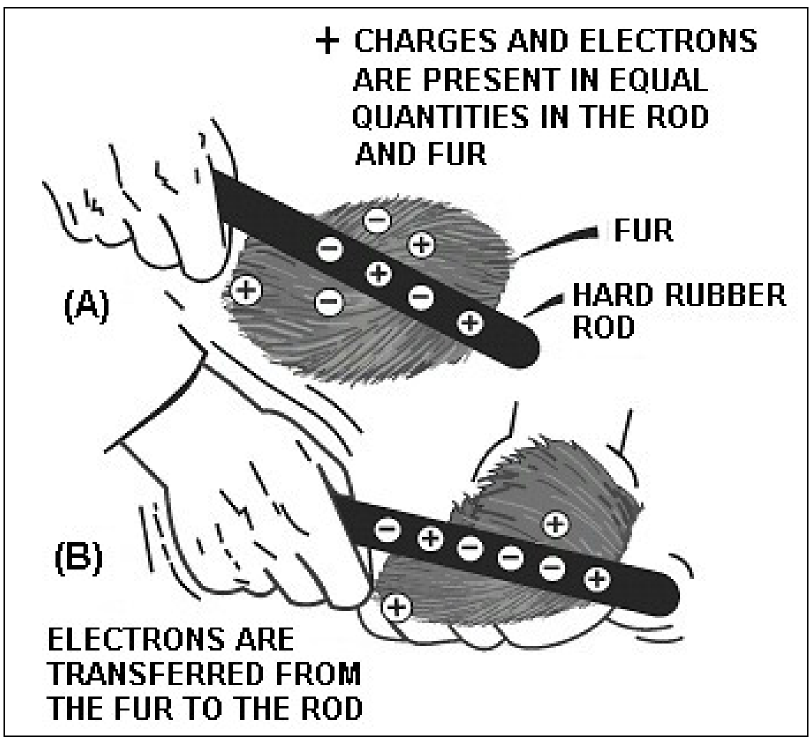

Figure 2-5. Producing Static Electricity by Friction

NATURE OF CHARGES

2-34. An atom, when in a natural or neutral state, has an equal number of electrons and protons. Due to this balance, the net negative charge of the electrons in orbit is exactly balanced by the net positive charge of the protons in the nucleus, making the atom electrically neutral.

2-35. An atom becomes a positive ion whenever it loses an electron and has an overall positive charge. However, when an atom acquires an extra electron, it becomes a negative ion and has a negative charge.

2-36. Due to normal molecular activity, ions are always present in any material. If the number of positive ions and negative ions is equal, the material is electrically neutral. When the number of positive ions exceeds the number of negative ions, the material is positively charged. The material is negatively charged whenever the negative ions outnumber the positive ions.

2-37. Since ions are actually atoms without their normal number of electrons. The excess or lack of electrons in a substance determines its charge. In most solids, the transfer of charges is by movement of electrons rather than ions. The transfer of charges by ions is more significant when considering the electrical activity in liquids and gases.

CHARGED BODIES

2-38. A fundamental law of electricity is that like charges repel each other and unlike charges attract each other. A positive charge and negative charge, being unlike, tend to move toward each other. In the atom, the negative electrons are drawn toward the positive protons in the nucleus. This attractive force is balanced by the electron’s centrifugal force caused by its rotation about the nucleus. As a result, the electrons remain in orbit and are not drawn into the nucleus. Electrons repel each other because of their like negative charges. Protons repel each other because of their like positive charges.

2-39. A simple experiment demonstrates the law of charged bodies. Suspend two pith (paper pulp) balls near one another by threads (see Figure 2-6). Rub a hard rubber rod with fur to give it a negative charge. Now, hold it against the right-handball (view A). The rod will give off a negative charge to the ball. The right-hand ball has a negative charge with respect to the left-hand ball. Release the two balls. They will be drawn together (view A). They will touch and remain in contact until the left-hand ball gains a portion of the negative charge of the right-handball. When this happens, they will swing apart. If a positive or a negative charge is placed on both balls (views B and C), the balls will repel each other.

COULOMB’S LAW OF CHARGES

2-40. A French scientist named Charles Coulomb first discovered the relationship between attracting and repelling charged bodies. Coulomb’s law states that charged bodies attract or repel each other with a force that is directly proportional to the product of their individual charges and inversely proportional to the square of the distance between them. The strength of the attracting or repelling force between two electrically charged bodies in free space depends on their charges and the distance between them.

ELECTRIC FIELDS

2-41. An electric field of force is the space between and around charged bodies in which their influence is felt. Electrostatic fields and dielectric fields are other names for this region of force.

2-42. Electric fields of force spread out in the space surrounding their point of origin. They generally diminish in proportion to the square of the distance from their source.

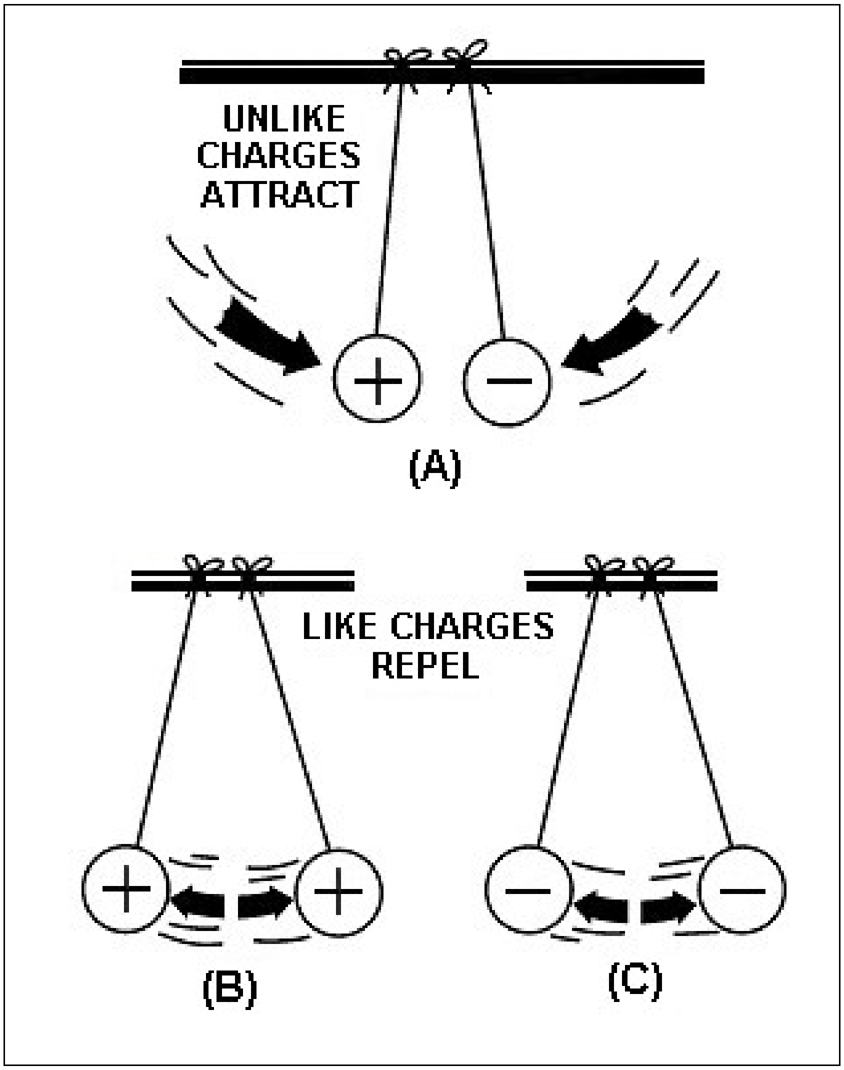

Figure 2-6. Reaction Between Charged Bodies

2-43. Imaginary lines, called electrostatic lines of force, are normally used in drawings to represent the field about a charged body. These imaginary lines represent the direction and strength of the field. To avoid confusion, the lines of force exerted by a positive charge are always shown leaving the charge. For a negative charge they are shown entering. Figure 2-7 shows these lines to represent the field about charged bodies. View A shows the repulsion of like-charged bodies and their associated fields. View B shows the attraction of unlike-charged bodies and their associated fields.

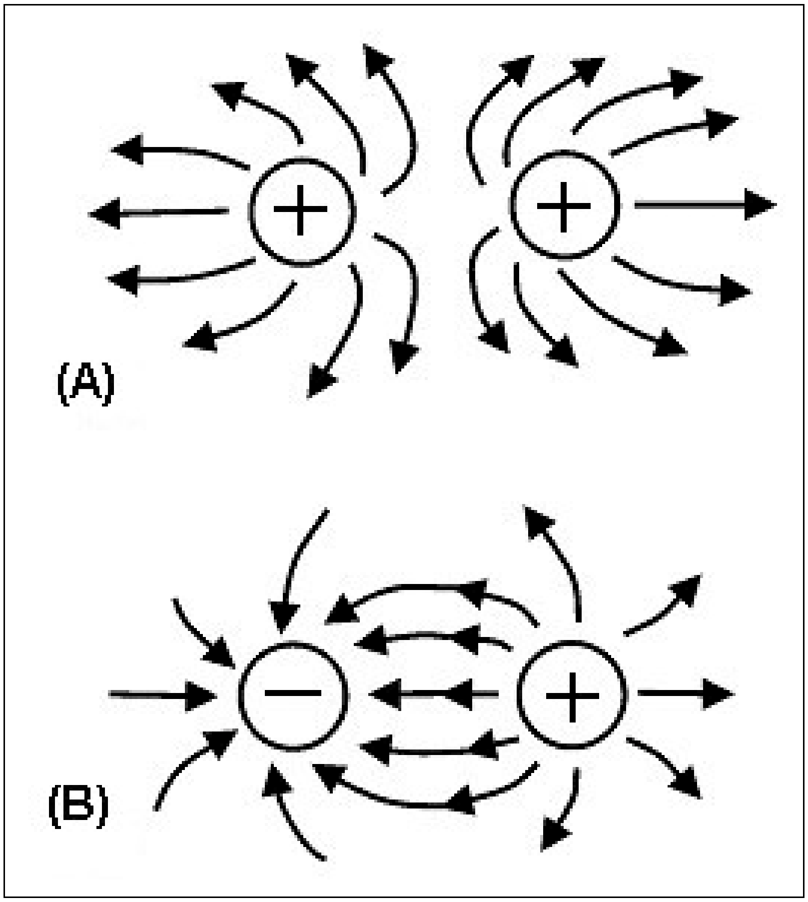

Figure 2-7. Lines of Force

MAGNETISM

2-44. To understand the principles of electricity, it is necessary to study magnetism and the effects of magnetism on electrical equipment. Magnetism and electricity are so closely related that the study of either subject would be incomplete without at least a basic knowledge of the other.

2-45. Much of today's modern electrical and electronic equipment could not function without magnetism. Modern computers, tape recorders, and video reproduction equipment use magnetized tape. High-fidelity speakers use magnets to convert amplifier outputs into audible sound. Electrical motors use magnets to convert electrical energy into mechanical motion. Generators use magnets to convert mechanical motion into electrical energy.

MAGNETIC MATERIALS

2-46. Magnetism is generally defined as that property of material that enables it to attract pieces of iron. A material possessing this property is a magnet. The word originated with the ancient Greeks who found stones with this characteristic. Materials that are attracted by a magnet (such as iron, steel, nickel, and cobalt) and that can become magnetized are called magnetic materials. Materials (such as paper, wood, glass, and tin) that are not attracted by magnets, are nonmagnetic. Nonmagnetic materials cannot become magnetized.

2-47. The most important materials connected with electricity and electronics are the ferromagnetic materials. Ferromagnetic materials are relatively easy to magnetize. They include iron, steel, cobalt, and the alloys Alnico and Permalloy. Combine two or more elements to make an alloy. One of these elements must be a metal. These new alloys can be very strongly magnetized. They can obtain a magnetic strength great enough to lift 500 times their own weight.

NATURAL MAGNETS

2-48. Magnetic stones (such as those found by the ancient Greeks) are natural magnets. These stones can attract small pieces of iron in a manner similar to the magnets common today. However, the magnetic properties attributed to the stones are products of nature and not the result of the efforts of man. The Greeks called these substances magnetite.

2-49. The Chinese are said to have been aware of some of the effects of magnetism as early as 2600 BC. They observed that stones similar to magnetite, when freely suspended, had a tendency to assume a nearly north and south direction. These stones are referred to lodestones or leading stones because of their directional quality.

2-50. Natural magnets, found in the United States, Norway, and Sweden, no longer have any practical use. It is now possible to easily produce more powerful magnets.

ARTIFICIAL MAGNETS

2-51. Magnets produced from magnetic materials are called artificial magnets. They can be made in a variety of shapes and sizes and are used extensively in electrical apparatus. Artificial magnets are generally made from special iron or steel alloys that are usually magnetized electrically. The material to be magnetized is inserted into a coil of insulated wire. Stroking a magnetic material with magnetite or with another artificial magnet will produce a heavy flow of electrons. The forces causing magnetization are represented by magnetic lines of force, very similar in nature to electrostatic lines of force.

2-52. Artificial magnets are usually classified as permanent or temporary, depending on their ability to retain their magnetic properties after the magnetizing force has been removed. Magnets made from substances (such as hardened steel and certain alloys that retain a great deal of their magnetism) are called permanent magnets. These materials are relatively difficult to magnetize because of the opposition offered to the magnetic lines of force as the lines of force try to distribute themselves throughout the material. The opposition is called reluctance.

All permanent magnets are produced from materials having a high reluctance.

2-53. A material with a low reluctance (such as soft iron or annealed silicon steel) is relatively easy to magnetize. However, it retains only a small part of its magnetism once the magnetizing force is removed. Materials that easily lose most of their magnetic strength are called temporary magnets. The amount of magnetism that remains in a temporary magnet is referred to as its residual magnetism. The ability of a material to retain an amount of residual magnetism is called the retentivity of the material.

2-54. The difference between a permanent and temporary magnet is indicated in terms of reluctance. A permanent magnet has a high reluctance and a temporary magnet has a low reluctance. Magnets are also described in terms of the permeability of their materials or the ease with which magnetic lines of force distribute themselves throughout the material. A permanent magnet, produced from a material with a high reluctance, has a low permeability. A temporary magnet, produced from a material with a low reluctance, has a high permeability.

MAGNETIC POLES

2-55. The magnetic force surrounding a magnet is not uniform. There is a great concentration of force at each end of the magnet and a very weak force at the center. To prove this fact, dip a magnet into iron filings (see Figure 2-8). Many filings will cling to the ends of the magnet, while very few stick to the center. The two ends, which are the regions of concentrated lines of force, are called the poles of the magnet. Magnets have two magnetic poles. Both poles have equal magnetic strength.

2-56. **Law of magnetic poles**. To demonstrate the law of magnetic poles, suspend a bar magnet freely on a string (see Figure 2-9). It will align itself in a north and south direction. Even when you repeat this experiment, the same pole of the magnet will always swing toward the north geographical pole of the earth. Therefore, it is called the north-seeking pole or simply the north pole. The other pole of the magnet is the south-seeking pole or the south pole.

2-57. A practical use of the directional characteristic of the magnet is the compass. The compass has a freely rotating magnetized needle indicator that points toward the north pole. The poles of a suspended magnet always move to a definite position. This indicates opposite magnetic polarity exists.

2-58. The law of electricity regarding the attraction and repulsion of charged bodies might also be applied to magnetism if the pole is considered as a charge. The north pole of a magnet will always be attracted to the south pole of another magnet and will show repulsion to another north pole. The law of magnetic poles is that like poles repel and unlike poles attract.

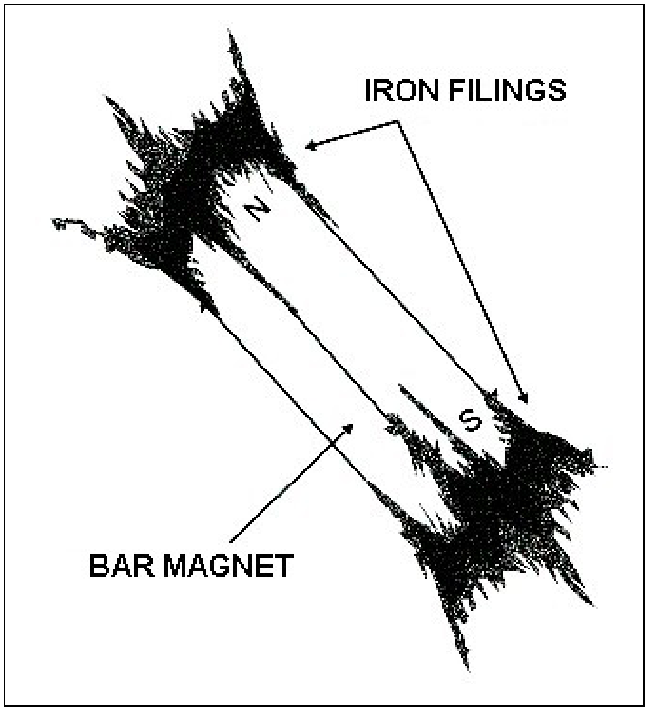

Figure 2-8. Iron Filings Cling to the Poles of a Magnet

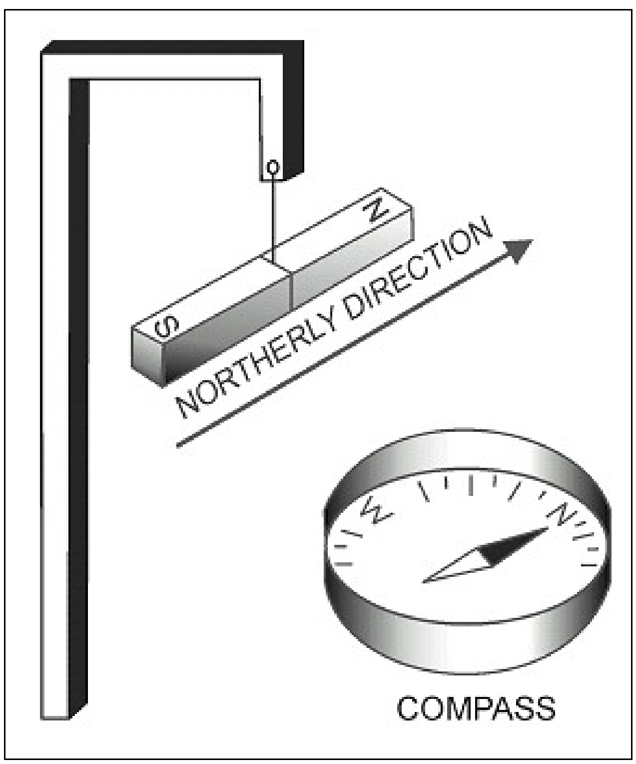

Figure 2-9. A Bar Magnet Acts as a Compass

2-59. **Earth's magnetic poles**. The fact that a compass needle always aligns itself in a particular direction, regardless of its location on earth, indicates that the earth is a huge natural magnet. The distribution of the magnetic force about the earth is the same as that which might be produced by a giant bar magnet running through the center of the earth (see Figure 2-10). The magnetic axis of the earth is about 15 degrees from its geographical axis, thereby locating the magnetic poles some distance from the geographical poles. The ability of the north pole of the compass needle to point toward the north geographical pole is due to the presence of the magnetic pole nearby. This magnetic pole of the earth is popularly considered the magnetic north pole. However, it actually must have the polarity of the magnet's south pole because it attracts the north pole of a compass needle. The reason for this conflict in terminology can be traced to the early users of the compass. Since they did not know that opposite magnetic poles attract, they called the end of the compass needle that pointed toward the north geographical pole the north pole of a compass needle. However, the north pole of a compass needle (a small bar magnet) can be attracted only by an unlike magnetic pole, a pole with the same magnetic polarity as the south pole of a magnet.

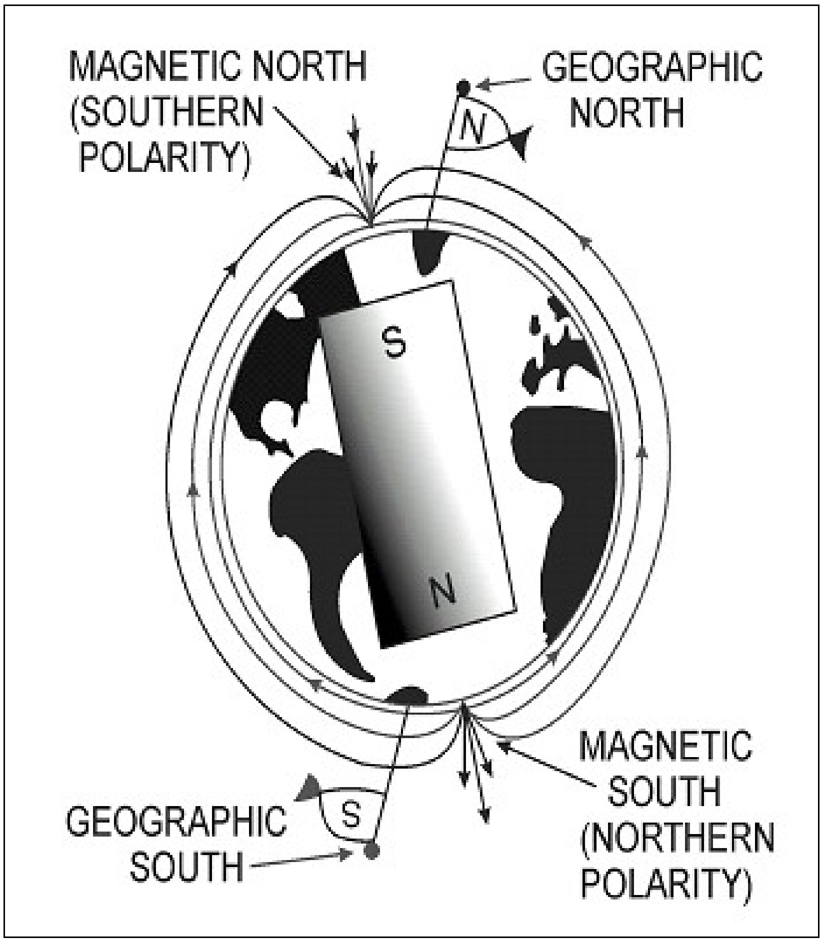

Figure 2-10. The Earth is a Magnet

THEORIES OF MAGNETISM

2-60. **Weber's theory**. A popular theory of magnetism considers the molecular alignment of the material. This is known as Weber's theory. This theory assumes that all magnetic substances are composed of tiny molecular magnets. Any magnetized material has the magnetic forces of its molecular magnets, thereby eliminating any magnetic effect. A magnetized material will have most of its molecular magnets lined up so that the north pole of each molecule points in one direction and the south pole faces the opposite direction. A material with its molecules so aligned will then have one effective north pole and one effective south pole. Figure 2-11 illustrates Weber's theory. When a steel bar is stroked several times in the same direction by a magnet, the magnetic force from the north pole of the magnet causes the molecules to align themselves.

2-61. **Domain theory**. A more modern theory of magnetism is based on the electron spin principle. All matter is composed of vast quantities of atoms, with each atom containing one or more orbital electrons. The electrons are considered to orbit in various shells and subshells depending on their distance from the nucleus. The structure of the atom has previously been compared to the solar system. The electrons orbiting the nucleus correspond to the planets orbiting the sun. Along with its orbital motion about the sun, each planet also revolves on its axis. It is believed that the electron also revolves on its axis as it orbits the nucleus of an atom.

2-62. An electron has a magnetic field about it along with an electric field. The number of electrons spinning in each direction determines the effectiveness of the magnetic field of an atom. If an atom has equal numbers of electrons spinning in opposite directions, the magnetic fields surrounding the electrons cancel one another and the atom is unmagnetized. However, if more electrons spin in one direction than another, the atom is magnetized. An atom with an atomic number of 26 (such as iron) has 26 protons in the nucleus and 26 revolving electrons orbiting its nucleus. If 13 electrons are spinning in a clockwise direction and 13 electrons are spinning in a counterclockwise direction, the opposing magnetic fields will be neutralized. When more than 13 electrons spin in either direction, the atom is magnetized. Figure 2-12 shows an example of a magnetized atom of iron.

Magnetic Fields

2-63. The space surrounding a magnet where magnetic forces act is the magnetic field. Magnetic forces have a pattern of directional force observed by performing an experiment with iron filings. Place a piece of glass over a bar magnet. Then sprinkle iron filings on the surface of the glass. The magnetizing force of the magnet will be felt through the glass and each iron filing becomes a temporary magnet. Tap the glass gently. The iron particles will align themselves with the magnetic field surrounding the magnet just as the compass needle did previously. The filings form a definite pattern, which is a visible representation of the forces comprising the magnetic field. The arrangements of iron filings in Figure 2-13 indicate that the magnetic field is very strong at the poles and weakens as the distance from the poles increases. They also show that the magnetic field extends from one pole to the other in a loop around the magnet.

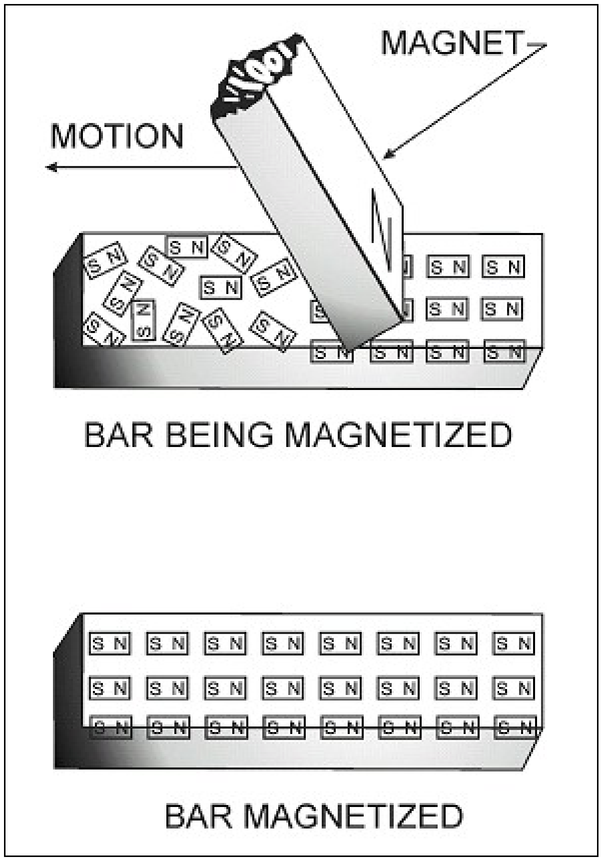

Figure 2-11. Molecular Magnets

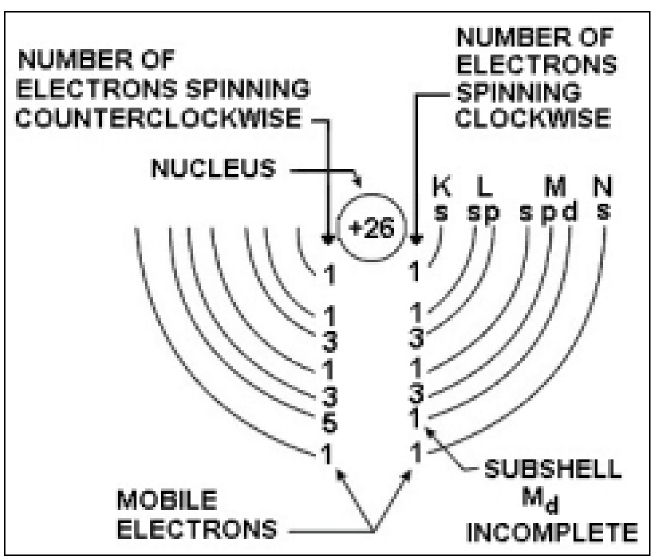

Figure 2-12. Magnetized Iron Atom

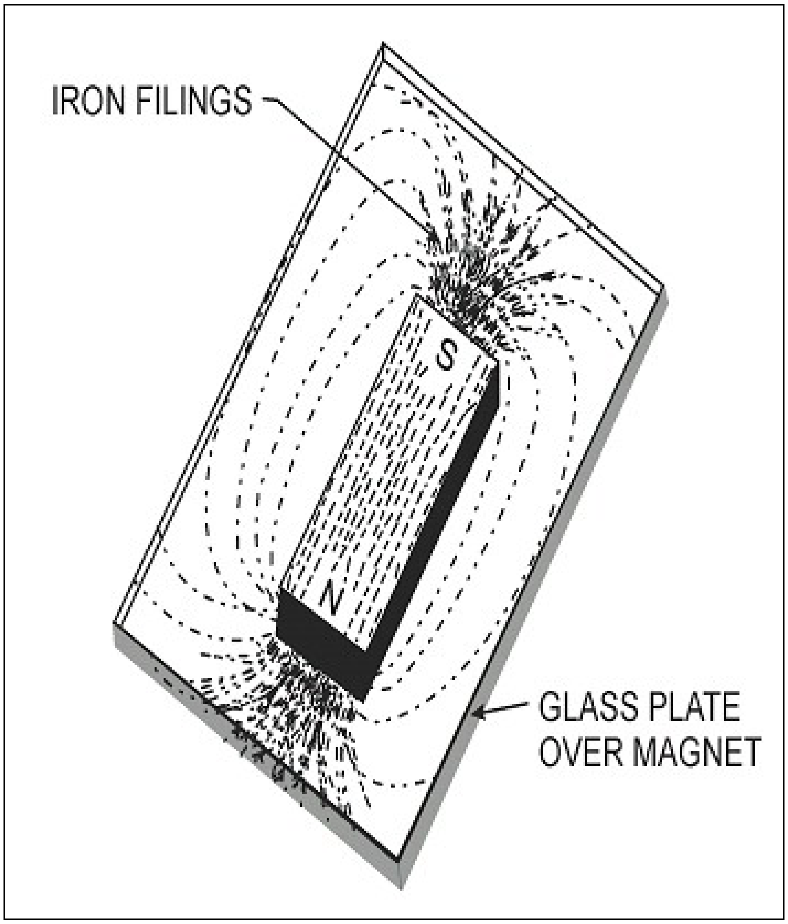

Figure 2-13. Pattern Formed by Iron Filings

Lines of Force

2-64. To further describe and work with magnetic phenomena, lines are used to represent the force existing in the area surrounding a magnet (see Figure 2-14). These magnetic lines of force are imaginary lines used to illustrate and describe the pattern of the magnetic field. The magnetic lines of force are assumed to emanate from the north pole of a magnet, pass through the surrounding space, and enter the south pole. They then travel inside the magnet from the south pole to the north pole, thereby completing a closed loop.

2-65. When two magnetic poles are brought close together, the mutual attraction or repulsion of the poles produces a more complicated pattern than that of a single magnet. Plot magnetic lines of force by placing a compass at various points throughout the magnetic field, or they can be roughly illustrated using iron filings as before. Figure 2-15 shows a diagram of magnetic poles placed close together.

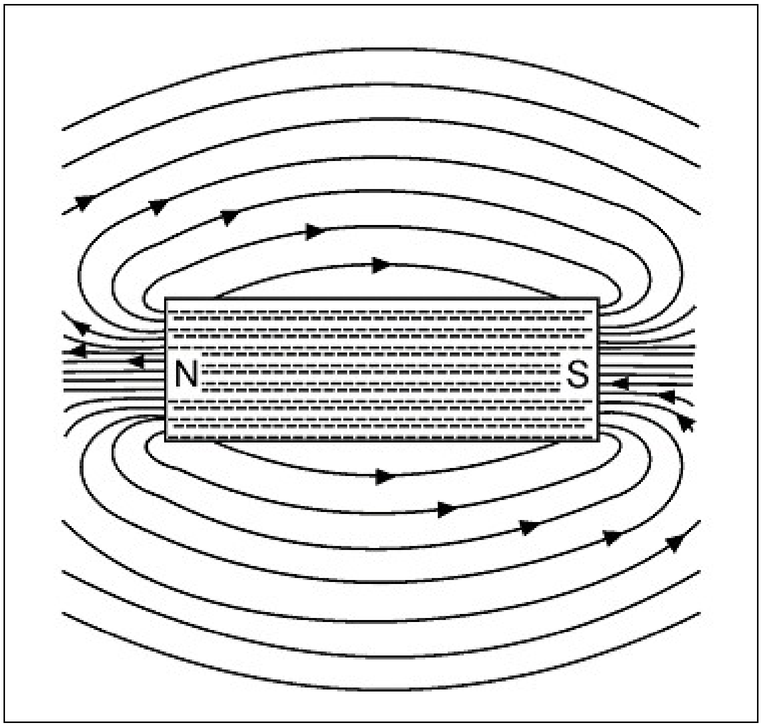

Figure 2-14. Bar Magnet Showing Lines of Force

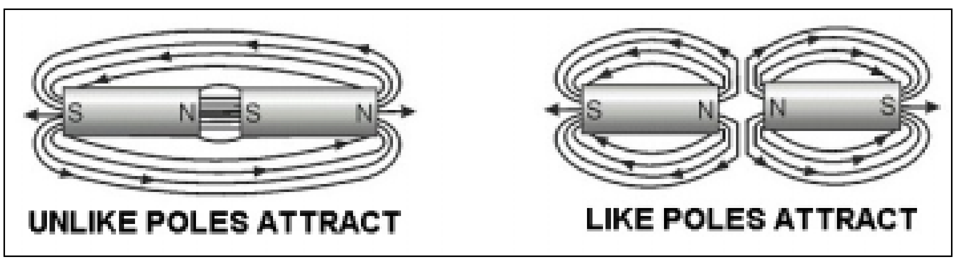

Figure 2-15. Magnetic Poles in Close Proximity

2-66. Although magnetic lines of force are imaginary, a simplified version of many magnetic phenomena can be explained by assuming that they have certain real properties. The lines of force are similar to rubber bands that stretch outward when a force is exerted on them and contract when the force is removed. The following are some of the characteristics of magnetic lines of force:

- They are continuous and will always form closed loops.
- They will never cross one another.
- They tend to shorten themselves. Therefore, the magnetic lines of force existing between two unlike poles cause the poles to be pulled together.
- They pass through all materials (both magnetic and nonmagnetic).

- They always enter or leave a magnetic material at right angles to the surface.
- Parallel magnetic lines of force traveling in the same direction repel one another. Parallel magnetic lines of force traveling in opposite directions extend to unite with each other and form single lines traveling in a direction determined by the magnetic poles creating the lines of force.

MAGNETIC EFFECTS

2-67. **Magnetic flux**. The total number of magnetic lines of force leaving or entering the pole of a magnet is called magnetic flux. The number of flux lines per unit area is called flux density.

2-68. **Field intensity**. The intensity of a magnetic field is directly related to the magnetic force exerted by the field.

2-69. **Attraction and repulsion**. The intensity of attraction or repulsion between magnetic poles may be described by a law almost identical to Coulomb's law of charged bodies law of charged bodies. The force between two poles is directly proportional to the product of the pole strengths and inversely proportional to the square of the distance between the poles.

Magnetic Induction

2-70. All substances that are attracted by a magnet can become magnetized. The fact that a magnet attracts material indicates the material must itself be a magnet at the time of attraction. Knowing about magnetic fields and magnetic lines of force simplifies the understanding of how a material becomes magnetized when brought near a magnet. As an iron nail is brought close to a bar magnet (see Figure 2-16), some flux lines emanating from the north pole of the magnet pass through the iron nail in completing their magnetic path. Since magnetic lines of force travel inside a magnet from the south pole to the north pole, the nail will be magnetized so its south pole will be adjacent to the north pole of the bar magnet.

2-71. If another nail is brought in contact with the end of the first nail, it is magnetized by induction. This process can be repeated until the strength of the magnetic flux weakens as distance from the bar magnet increases. However, as soon as the first iron nail is pulled away from the bar magnet, all the nails will fall. Each nail becomes a temporary magnet. However, once the magnetizing force is removed, the nail's domain once again assumes a random distribution.

2-72. Magnetic induction always produces a pole polarity on the material being magnetized opposite that of the adjacent pole of the magnetizing force. It is sometimes possible to bring a weak north pole of a magnet near a strong magnet north pole and note attraction between the poles. The weak magnet, when placed within the magnetic field of the strong magnet, has its magnetic polarity reversed by the field of the stronger magnet. Therefore, it is attracted to the opposite pole. For this reason, one should keep a very weak magnet (such as a compass needle) away from a very strong magnet.

2-73. Magnetism can be induced in a magnetic material by several means. The magnetic material may be placed in the magnetic field, brought into contact with a magnet, or stroked by a magnet. Stroking and contact both indicate actual contact with the material but are considered in magnetic studies as magnetizing by induction.

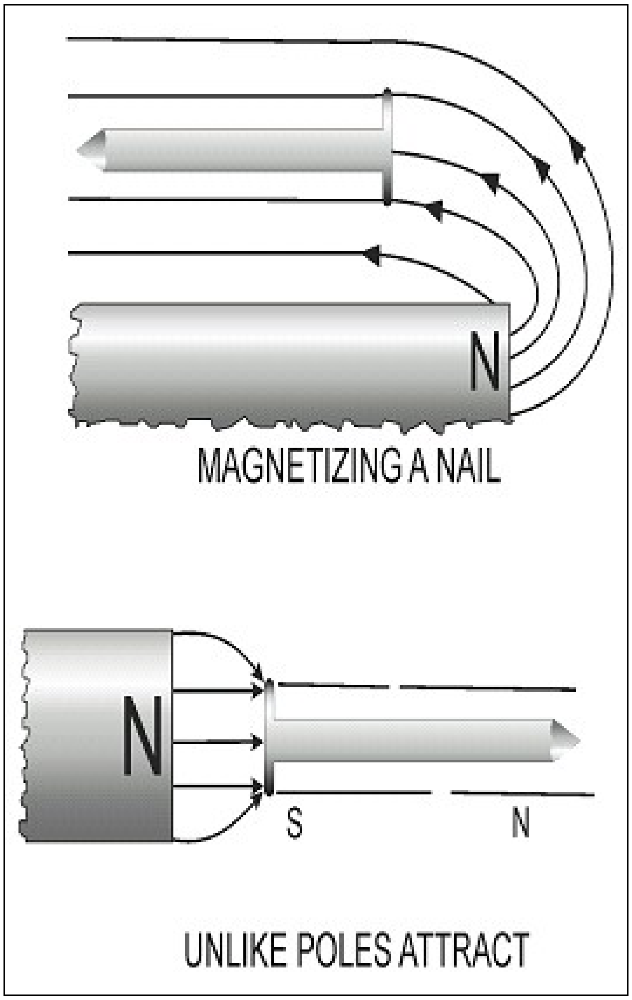

Figure 2-16. Magnetized Nail

Magnetic Shielding

2-74. Magnetic flux has no known insulator. If a nonmagnetic material is placed in a magnetic field, there is no appreciable change in flux. That is, the flux penetrates the nonmagnetic material. For example, a glass plate placed between the poles of a horseshoe magnet will have no appreciable effect on the field, although glass itself is a good insulator in an electric circuit. If a magnetic material (such as soft iron) is placed in a magnetic field, the flux may be redirected to take advantage of the greater permeability of the magnetic material (see Figure 2-17). Permeability is the quality of a substance that determines the ease with which it can be magnetized.

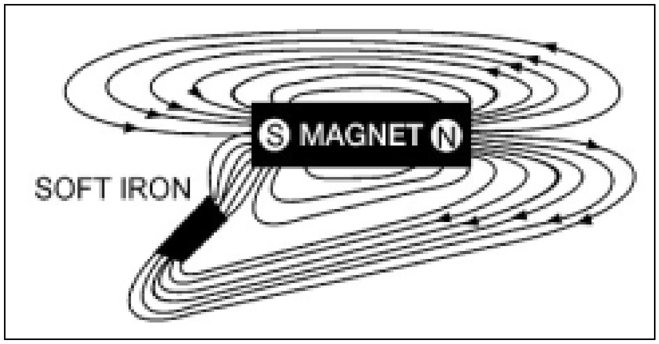

Figure 2-17. Effects of a Magnetic Substance in a Magnetic Field

2-75. Stray magnetic fields can influence the sensitive mechanisms of electric instruments and meters, causing errors in their readings. Instrument mechanisms cannot be insulated against magnetic flux. Therefore, the flux must be directed around the instrument by placing a soft-iron case, called a magnetic screen or magnetic shield, about the instrument. Since the flux is established more readily through the iron (even though the path is larger) than through the air inside the case, the instrument is effectively shielded. Figure 2-18 shows a soft iron magnetic shield around a watch.

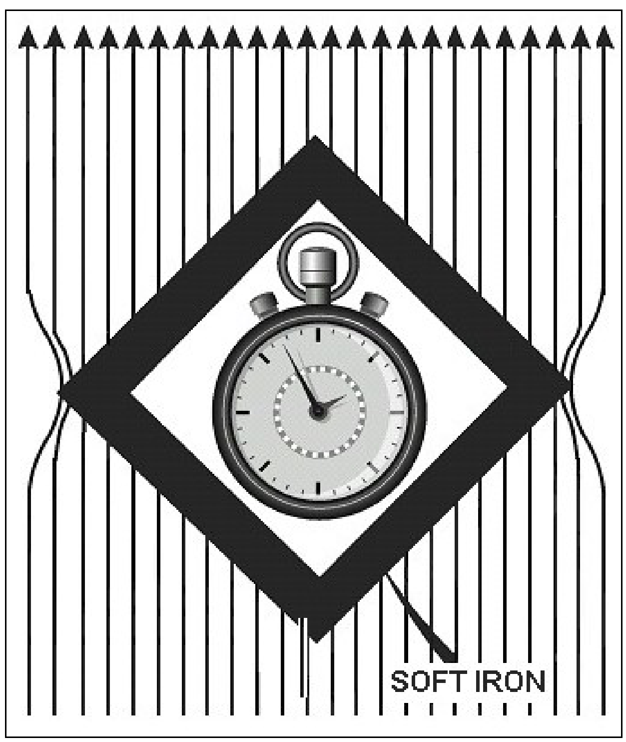

Figure 2-18. Magnetic Shield

Magnetic Shapes

2-76. Magnets, because of their many uses, are found in various shapes and sizes. However, they usually come under one of three general classifications: bar, ring, or horseshoe magnets.

2-77. The bar magnet is most often used in schools and laboratories for studying the properties and effects of magnetism. The bar magnet helped demonstrate magnetic effects in Figure 2-14.

2-78. The ring magnet is used for computer memory cores. A common application for a temporary ring magnet is the shielding of electrical instruments.

2-79. The horseshoe magnet is most frequently used in electrical and electronic equipment. A horseshoe magnet is similar to a bar magnet but is bent in the shape of a horseshoe. The horseshoe magnet is magnetically stronger than a bar magnet of the same size and material because the magnetic poles are closer together. The magnetic strength from one pole to the other is greatly increased because the magnetic field is concentrated in a smaller area. Electrical measuring devices often use horseshoe magnets.

Care of Magnets

2-80. A piece of steel that has been magnetized can lose much of its magnetism by improper handling. If it is jarred or heated, its domains will be misaligned and it loses some of its effective magnetism. If this piece of steel forms the horseshoe magnet of a meter, the meter will no longer operate or will give inaccurate readings. Therefore, be careful when handling instruments containing magnets. Severe jarring or subjecting the instrument to high temperatures will damage the device.

2-81. A magnet may also become weakened from loss of flux. Always try to avoid excess leakage of magnetic flux when storing magnets. Always store a horseshoe magnet with a keeper. A keeper is a soft iron bar used to join the magnetic poles. By storing the magnet with a keeper, the magnetic flux continuously circulates through the magnet and does not leak off into space.

2-82. When storing bar magnets, follow the same principle. Always store bar magnets in pairs with a north pole and a south pole placed together. This provides a complete path for the magnetic flux without any flux leakage.

ENERGY AND WORK

2-83. In the field of physical science, work is defined as the product of force and displacement. That is, the force applied to move an object and the distance the object is moved are the factors of work performed. No work is accomplished unless the force applied causes a change in position of a stationary object or a change in the velocity of a moving object. For example, a worker may tire by pushing against a heavy wooden crate, but unless the crate moves, no work will be accomplished.

2-84. In the study of energy and work, energy is defined as the ability to do work. To perform any kind of work, energy must be expended (converted from one form to another). Energy supplies the required force or power whenever any work is accomplished.

2-85. One form of energy is that contained by an object in motion. When a hammer is set in motion in the direction of a nail, it possesses energy of motion. As the hammer strikes the nail, the energy of motion is converted into work as the nail is driven into the wood. The distance the nail is driven into the wood depends on the velocity of the hammer at the time it strikes the nail. Energy contained in an object due to its motion is called kinetic energy.

2-86. If a hammer is suspended one meter above a nail by a string, gravity will pull the hammer downward. If the string is suddenly cut, the force of gravity will pull the hammer down against the nail, driving it into the wood. While the hammer is suspended above the nail, it has the ability to do work because of its elevated position in the earth's gravitational field. Since energy is the ability to do work, the hammer contains energy.

2-87. Energy contained in an object because of its position is called potential energy. The amount of potential energy available equals the product of the force required to elevate the hammer and the height to which it is elevated.

2-88. Another example of potential energy is that contained in a tightly coiled spring. The amount of energy released when the spring unwinds depends on the amount of force required to wind the spring initially.

ELECTRICAL CHARGES

2-89. The study of electrostatics shows that a field of force exists in the space surrounding any electrical charge. The strength of the field depends directly on the force of the charge.

2-90. The charge of one electron might be used as a unit of electrical charge because displacing electrons creates charges. However, the charge of one electron is so small that it is impractical to use. The practical unit adopted for measuring charges is the coulomb, named after the scientist Charles Coulomb. A coulomb equals the charge 6,242,000,000,000,000,000 (six quintillion, two hundred forty-two quadrillion or 6.242 times 10 to the 18^{th} power) electrons.

2-91. When a charge of 1 coulomb exists between two bodies, one unit of electrical potential energy exists. This difference in potential between the two bodies is called electromotive force or voltage. The unit of measure is the volt.

2-92. Electrical charges are created by the displacement of electrons, so that there is an excess of electrons at one point and a deficiency at another point. Therefore, a charge must always have either a negative or positive polarity. A body with an excess of electrons is negative while a body with a deficiency of electrons is positive.

2-93. A difference in potential can exist between two points or bodies only if they have different charges. In other words, there is no difference in potential between two bodies if both have a deficiency of electrons to the same degree. However, if one body is deficient by 6 coulombs (6 volts) and the other is deficient by 12 coulombs (12 volts), the difference in potential is 6 volts. The body with the greater deficiency is positive with respect to the other.

2-94. In most electrical circuits only the difference in potential between two points is important. The absolute potentials of the points are of little concern. Often it is convenient to use one standard reference for all of the various potentials throughout a piece of equipment. Therefore, the potentials at various points in a circuit are generally measured with respect to the metal chassis on which all parts of the circuit are mounted. The chassis is considered to be at zero potential and all other potentials are either positive or negative with respect to the chassis. When used as the reference point, the chassis is said to be at ground potential.

2-95. Sometimes rather large values of voltage may be encountered and the volt becomes too small a unit for convenience. In this situation, the kilovolt, meaning 1,000 volts, is used. For example, 20,000 volts would be written as 20 kV. Sometimes the volt may be too large a unit when dealing with very small voltages. For this purpose, the millivolt, meaning one-thousandth of a volt and the microvolt, meaning one-millionth of a volt, are used. For example, 0.001 volt would be written as 1 mV and 0.000025 volt would be written as 25 μV.

2-96. When a difference in potential exists between two charged bodies connected by a conductor, electrons will flow along the conductor. This flow is from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

2-97. Figure 2-19 shows an analogy of this action in the two water tanks connected by a pipe and valve. At first, the valve is closed and all the water is in tank A. Therefore, the water pressure across the valve is at maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe because there is no longer a difference in water pressure between the two tanks. Electron movement through an electric circuit is directly proportional to the difference in potential, or EMF, across the circuit, just as the flow of water through the pipe in Figure 2-19 is directly proportional to the difference in water level in the two tanks.

2-98. A fundamental law of electricity is that the electron flow is directly proportional to the applied voltage. If the voltage is increased, the flow is increased. If the voltage is decreased, the flow is decreased.

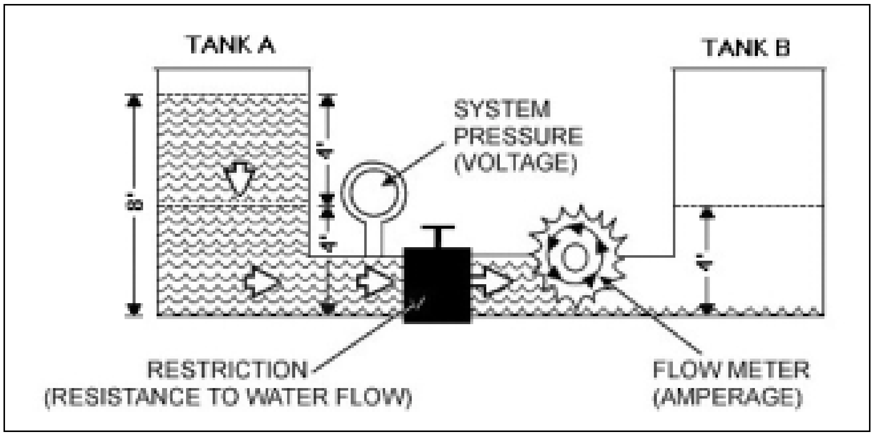

Figure 2-19. Water Analogy of Electric Difference in Potential

VOLTAGE PRODUCTION

2-99. It has been demonstrated that rubbing a rubber rod with fur produces a charge. The rod acquires electrons from the fur because of the friction involved, making it negative. The fur becomes positive due to the loss of electrons. These quantities of charge constitute a difference in potential between the rod and the fur. The electrons that make up this difference in potential are capable of doing work if a discharge is allowed to occur.

2-100. To be a practical source of voltage, the potential difference must not be allowed to dissipate. It must be maintained continuously. As one electron leaves the concentration of negative charge, another must be immediately provided to take its place. If not, the charge will eventually diminish to the point where no further work can be accomplished. Therefore, a voltage source is a device that can supply and maintain voltage while an electrical apparatus is connected to its terminals. The internal action of the source is such that electrons are continuously removed from one terminal to keep it positive and simultaneously supplied to the second terminal to keep it negative.

2-101. Presently, six methods for producing a voltage or EMF are known. Some are more widely used than others and some are used mostly for specific applications. The following are the six known methods of producing a voltage:

- **Friction.** Rubbing certain materials together produces voltage.
- **Pressure (piezoelectricity).** Squeezing crystals of certain substances produces voltage.
- **Heat (thermoelectricity).** Heating the joint (junction) where two unlike metals are joined produces voltage.
- **Light (photoelectricity).** Light striking photosensitive (light sensitive) substances produces voltage.

- **Chemical action.** Chemical reaction in a battery cell produces voltage.
- **Magnetism.** A conductor moving through a magnetic field or a magnetic field moving through a conductor so that the magnetic lines of force of the field are cut produces voltage.

VOLTAGE PRODUCED BY FRICTION

2-102. The first method discovered for creating a voltage was generation by friction. The development of charges by rubbing a rod with fur is a prime example of the way friction generates voltage. This voltage cannot be conveniently used or maintained because of the nature of the materials producing the voltage. Therefore, this method has very little practical use.

2-103. While searching for ways to produce larger amounts of voltage with more practical nature, researchers developed machines to transfer charges from one terminal to another by rotating glass discs or moving belts. The most notable of these machines is the Van de Graaff generator. It is used today to produce potentials in the order of millions of volts for nuclear research. Since these machines have little value outside the field of research, their theory of operation will not be described here.

VOLTAGE PRODUCED BY PRESSURE

2-104. One specialized method of generating an EMF uses the characteristics of certain ionic crystals such as quartz, Rochelle salts, and tourmaline. These crystals can generate a voltage whenever stresses are applied to their surfaces. Therefore, if a crystal of quartz is squeezed, charges of opposite polarity appear on two opposite surfaces of the crystal. If the force is reversed and the crystal is stretched, charges again appear but are of the opposite polarity from those produced by squeezing. If a crystal of this type is vibrated, it produces a voltage of reversing polarity between two of its sides. Quartz or similar crystals can therefore be used to convert mechanical energy into electrical energy. Figure 2-20 shows this phenomenon, called the piezoelectric effect. Some of the common devices that use piezoelectric crystals are microphones and oscillators used in radio transmitters, radio receivers, and sonar equipment. This method of generating an EMF is not suitable for applications having large voltage or power requirements. However, it is widely used in sound and communications systems where small signal voltages can be effectively used.

2-105. Crystals of this type also possess another interesting property, the converse piezoelectric effect. They can convert electrical energy into mechanical energy. A voltage impressed across the proper surfaces of the crystal will cause it to expand or contract its surfaces in response to the voltage applied.

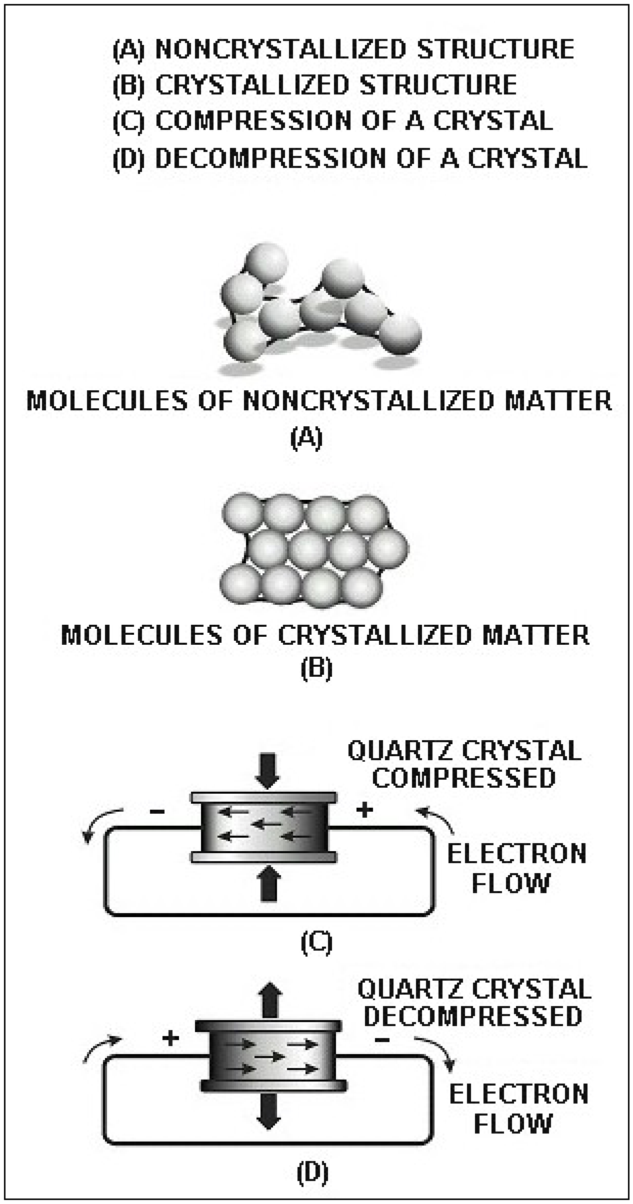

Figure 2-20. Piezoelectric Effect

VOLTAGE PRODUCED BY HEAT

2-106. When a length of metal (such as copper) is heated at one end, valence electrons tend to move away from the hot end toward the cooler end. This is true of most metals. However, in some metals (such as iron) the opposite takes place and electrons tend to move toward the hot end. Figure 2-21 illustrates these characteristics. The negative charges (electrons) are moving through the copper away from the heat and through the iron toward the heat. They cross from the iron to the copper through the current meter to the iron at the cold junction. This device is called a thermocouple.

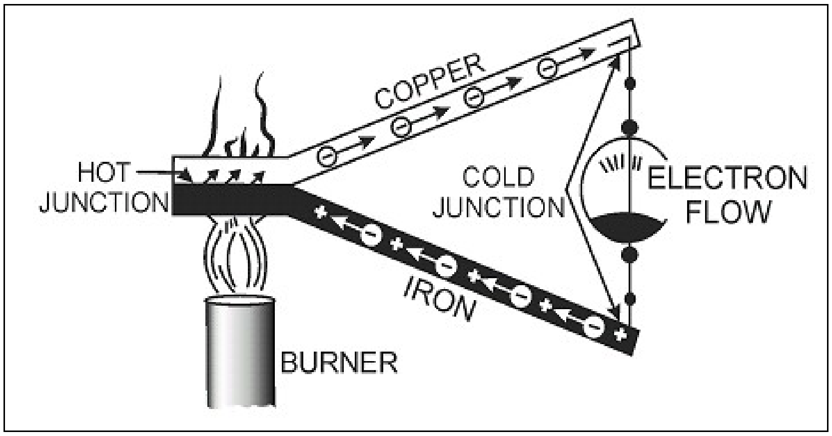

Figure 2-21. Voltage Produced by Heat

2-107. Thermocouples have a greater power capacity than crystals. However, they are still very small compared to some other sources. The thermoelectric voltage in a thermocouple depends mainly on the difference in temperature between the hot and cold junctions. They are therefore widely used to measure temperature and are used in heat-sensing devices in automatic temperature control equipment. Thermocouples generally can be subjected to greater temperatures then ordinary thermometers, such as mercury or alcohol types.

VOLTAGE PRODUCED BY LIGHT

2-108. Light, when it strikes the surface of a substance, may dislodge electrons from their orbits around the surface atoms of the substance. This dislodging of electrons occurs because light has energy, the same as any moving force. Some substances, mostly metallic ones, are far more sensitive to light than others. That is, more electrons are dislodged and emitted from the surface of a highly sensitive metal, with a given amount of light, than are emitted from a less sensitive substance. Upon losing electrons, the photosensitive (light-sensitive) metal becomes positively charged and an electric force is created. Voltage produced in this manner is called photoelectric voltage.

2-109. The photosensitive materials most commonly used to produce a photoelectric voltage are various compounds of silver oxide or copper oxide. A complete device that operates with photoelectric voltage is a photoelectric cell. Many different sizes and types of photoelectric cells are in use and each serves the special purpose for which it is designed. However, nearly all of them have some of the basic features of the photoelectric cells (see Figure 2-22, views A and B).

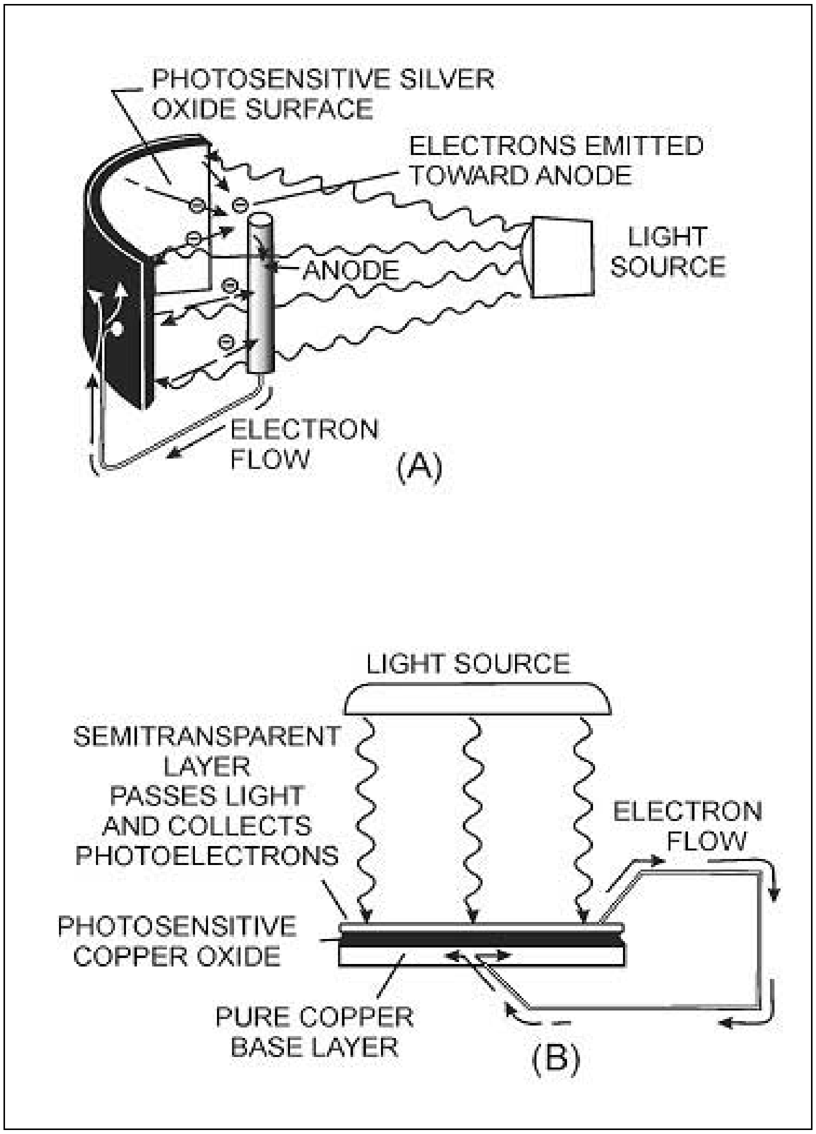

Figure 2-22. Voltage Produced by Light

2-110. The cell in view A has a curved, light-sensitive surface focused on the central anode. When light from the direction shown strikes the sensitive surface, it emits electrons toward the anode. The more intense the light, the greater the number of electrons emitted. When a wire is connected between the filament and the back, or dark side of the cell, the accumulated electrons will flow to the dark side. These electrons will eventually pass through the metal of the reflector and replace the electrons leaving the light-sensitive surface. Therefore, light energy is converted to a flow of electrons and a usable current is developed.

2-111. The cell in view B is constructed in layers. A base plate of pure copper is coated with light-sensitive copper oxide. An extremely semitransparent layer of metal is placed over the copper oxide. This additional layer serves two purposes:

- It permits the penetration of light to the copper oxide.
- It collects the electrons emitted by the copper oxide.

2-112. An externally connected wire completes the electron path, the same as in the reflector-type cell. The photoelectric cell's voltage is used as needed by connecting the external wires to some other device, which amplifies (enlarges) it to a usable level.

2-113. The power capacity of a photoelectric cell is very small. However, it reacts to light-intensity variations in an extremely short time. This characteristic makes the photoelectric cell very useful in detecting or accurately controlling many operations. For instance, the photoelectric cell, or some form of the photoelectric principle, is used in television cameras, automatic manufacturing process controls, door openers, and burglar alarms.

VOLTAGE PRODUCED BY CHEMICAL ACTION

2-114. Voltage may be produced chemically when certain substances are exposed to chemical action. If two dissimilar substances, usually metals or metallic materials, are immersed in a solution that produces a greater chemical action on one substance than on the other, a difference in potential exists between the two. If a conductor is then connected between them, electrons flow through the conductor to equalize the charge. This arrangement is called a primary cell. The two metallic pieces are electrodes and the solution is the electrolyte. The voltaic cell in Figure 2-23 is a simple example of a primary cell. The difference in potential results from the fact that material from one or both of the electrodes goes into the electrolyte. In the process, ions form near the electrodes. Due to the electric field associated with the charged ions, the electrodes acquire charges. The amount of difference in potential between the electrodes depends mainly on the metals used.

2-115. The two types of primary cells are the wet cell and the dry cell. In a wet cell, the electrolyte is a liquid. A cell with a liquid electrolyte must remain in an upright position and is not readily transportable. An automotive battery is an example of this type of cell. The dry cell is more commonly used than the wet cell. The dry cell is not actually dry, but it contains an electrolyte mixed with other materials to form a paste. Flashlights and portable radios are commonly powered by dry cells.

2-116. Batteries are formed when several cells are connected together to increase electrical output. See Chapter 4 for a more in-depth discussion on batteries.

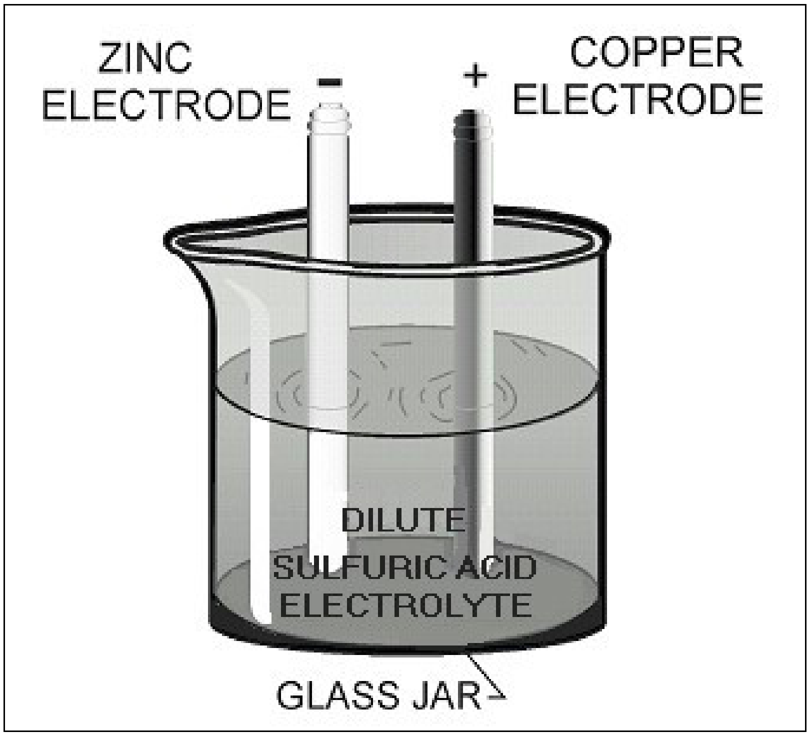

Figure 2-23. Voltaic Cell

VOLTAGE PRODUCED BY MAGNETISM

2-117. Magnets or magnetic devices are used for thousands of different jobs. One of the most useful and widely employed applications of magnets is to produce vast quantities of electric power from mechanical sources. A number of different sources (such as gasoline or diesel engines and water or steam turbines) may provide the mechanical power. Using the principle of electromagnetic induction, the final conversion of these source energies is done by generators. There are many types and sizes of these generators.

2-118. Three fundamental conditions must exist before a voltage can be produced by magnetism:

- There must be a conductor in which the voltage will be produced.
- There must be a magnetic field in the conductor's vicinity.
- There must be relative motion between the field and conductor. The conductor must be moved so it cuts across the magnetic lines of force, or the field must be moved so the conductor cuts the lines of force.

2-119. When a conductor or conductors move across a magnetic field and cut the lines of force, electrons within the conductor are propelled in one direction or another. This creates an electric force or voltage.

2-120. Figure 2-24 shows the three conditions needed to create an induced voltage. There is a magnetic field between the poles of the C-shaped magnet. The copper wire is the conductor. The wire is moved back and forth across the magnetic field for relative motion.

2-121. In view A, the conductor moves toward the front of the page and the electrons move from left to right. The movement of the electrons occurs because of the magnetically induced EMF acting on the electrons in the copper. The right-hand end becomes negative and the left-hand end positive. The conductor is stopped in view B and motion is eliminated (one of the three required conditions). Since there is no longer an induced EMF, there is no longer any difference in potential between the two ends of the wire. In view C, the conductor is moving away from the front of the page. An induced EMF is again created. However, the reversal of motion has caused a reversal of direction in the induced EMF.

2-122. If a path for electron flow is provided between the ends of the conductor, electrons will leave the negative end and flow to the positive end. View D shows this condition. Electron flow will continue as long as the EMF exists. Holding the conductor stationary and moving the magnetic field back and forth will also create the induced EMF (see Figure 2-24).

ELECTRIC CURRENT

2-123. Electrons move through a conductor in response to a magnetic field. Electron current is the directed flow of electrons. The direction of electron movement is from a region of negative potential to a region of positive potential. Therefore, electron current flow in a material is determined by the polarity of the applied voltage.

RANDOM DRIFT

2-124. All materials are composed of atoms, each capable of being ionized. If some form of energy (such as heat) is applied to a material, some electrons acquire enough energy to move to a higher energy level. As a result, some electrons are freed from their parent atoms, which then become ions. Other forms of energy, particularly light or an electric field, will also cause ionization.

2-125. The number of free electrons resulting from ionization depends on the quantity of energy applied to a material and the atomic structure of the material. At room temperature, some materials that are classified as conductors have an abundance of free electrons while materials classified as insulators exchange relatively few free electrons.

2-126. In a study of electric current, conductors are of major concern. Conductors consist of atoms with loosely bound electrons in their outer orbits. Due to the effects of increased energy, these outermost electrons frequently break away from their atoms and freely drift throughout the material. The free electrons take an unpredictable path and drift haphazardly about the material. This movement is called random drift. Random drift of electrons occurs in all materials. The degree of random drift is greater in a conductor than in an insulator.

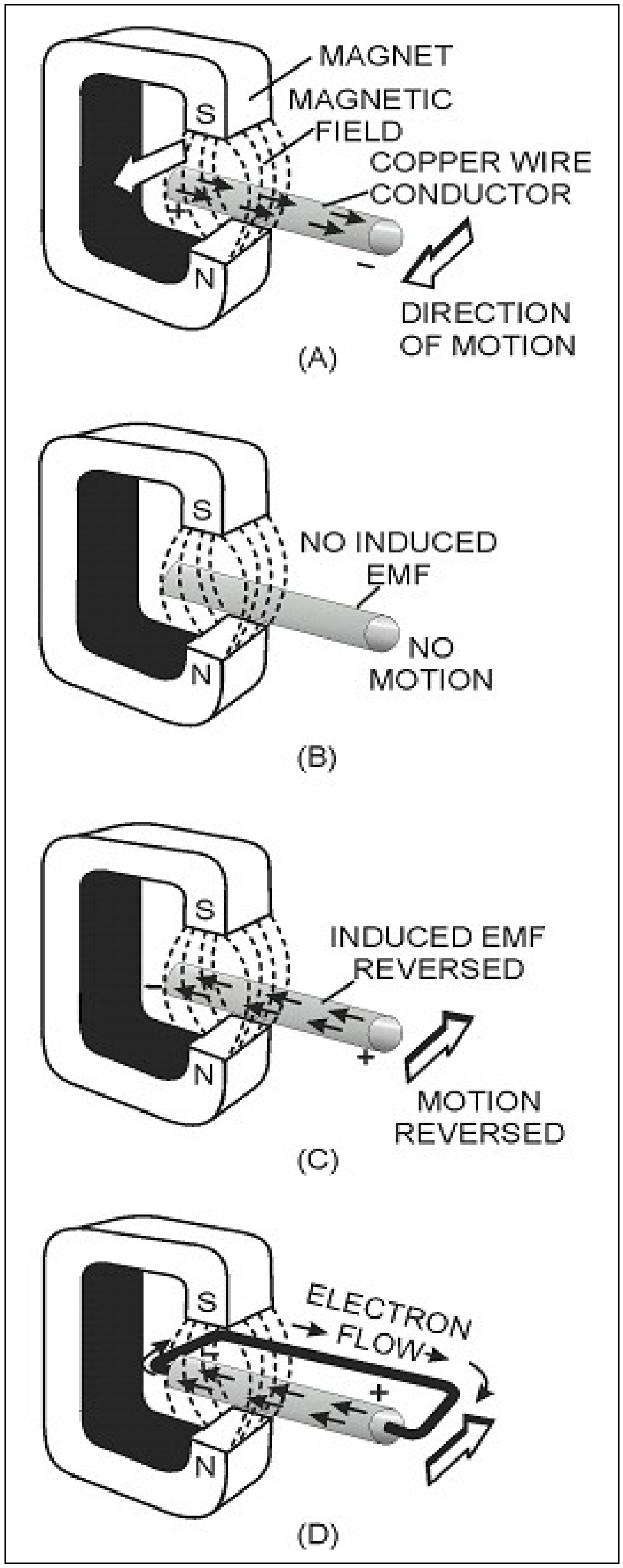

Figure 2-24. Voltage Produced by Magnetism

DIRECTED DRIFT

2-127. Every charged body has an associated electrostatic field. Bodies with like charges repel one another and bodies with unlike charges attract each other. An electron is effectively an electrostatic field in the same manner as any negatively charged body (it is repelled by a negative charge and attracted by a positive charge). If a conductor has a difference in potential impressed across it, a direction is imparted to the random drift (see Figure 2-25), causing the free electrons to be repelled away from the negative terminal and attracted toward the positive terminal. This effect constitutes a general migration of electrons from one end of the conductor to the other. The directed migration of free electrons due to the potential difference is called directed drift.

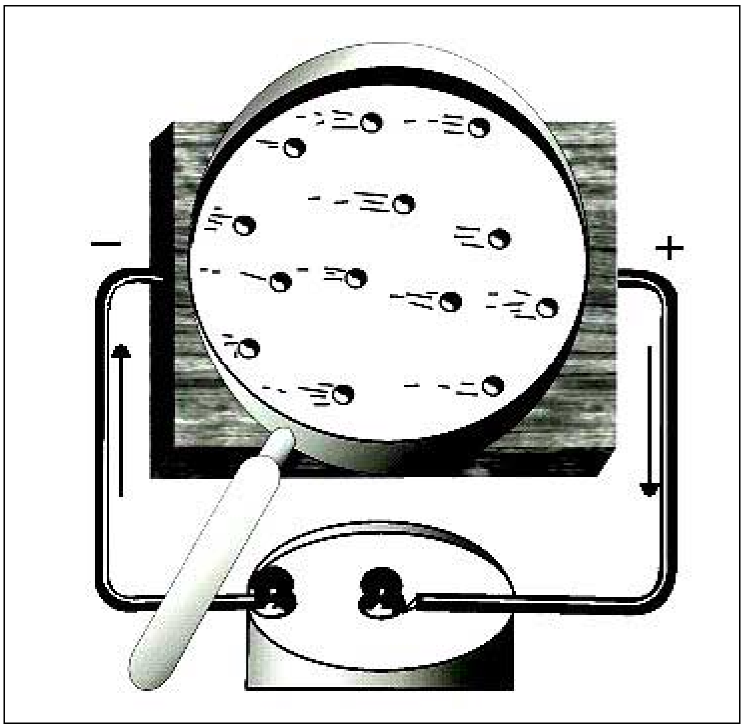

Figure 2-25. Directed Drift

2-128. The directed movement of the electrons occurs at a relatively low velocity (rate of motion in a particular direction). However, the effect of this directed movement is almost instantaneous (see Figure 2-26). As a difference in potential is impressed across the conductor, the positive terminal of the battery attracts electrons from point A. Point A now has a deficiency of electrons. As a result, electrons are attracted from point B to point A. Point B now has an electron deficiency. Therefore, it will attract electrons. This same effect occurs throughout the conductor. At the same instant the positive battery terminal attracts electrons from point A, the negative terminal repels electrons toward point D. These electrons are attracted to point D as it gives up electrons to point C. This process continues for as long as a difference in potential exists across the conductor. Although an individual electron moves quite slowly through the conductor, the effect of a directed drift occurs almost instantly. As an electron moves into the conductor at point D, an electron is leaving at point A. This action takes place at approximately the speed of light.

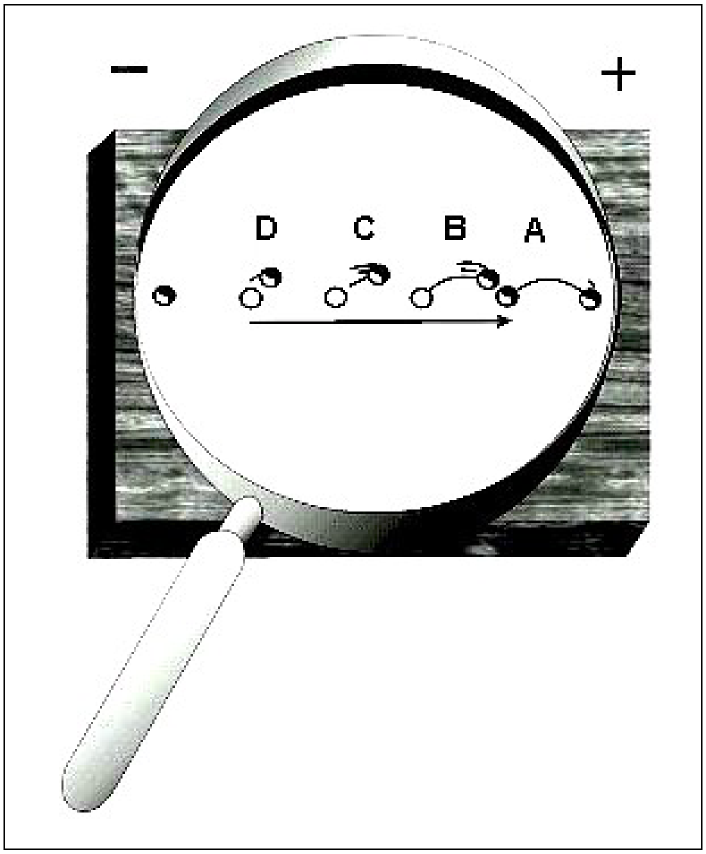

Figure 2-26. Effect of Directed Drift

MAGNITUDE OF CURRENT FLOW

2-129. Electric current is the directed movement of electrons. Therefore, directed drift is current and the terms can be used interchangeably. The term "directed drift" helps distinguish the random and directed motion of electrons. However, "current flow" is the term most commonly used to indicate a directed movement of electrons.

2-130. The magnitude of current flow is directly related to the amount of energy that passes through a conductor as a result of the drift action. An increase in the number of energy carriers (moving free electrons) or an increase in the energy of the existing valence electrons increases the current flow. When an electric potential is impressed across a conductor, the velocity of the free electrons increases, causing an increase in the energy of the carriers. An increased number of electrons are also generated, providing added carriers of energy. The additional number of free electrons is relatively small. Therefore, the magnitude of current flow depends mainly on the velocity of the existing moving electrons.

2-131. The difference in potential affects the magnitude of current flow. Initially, free electrons are given additional energy because of the repelling and attracting electrostatic field. If the difference in potential (voltage) is increased, the electric field will be stronger. Also, the amount of energy imparted to a valence electron will be greater and the current will be increased. If the potential difference is decreased, the strength of the field is reduced, the energy supplied to the electron is diminished, and the current is decreased.

MEASUREMENT OF CURRENT

2-132. The magnitude of current is measured in amperes. A current of 1 ampere is said to flow when 1 coulomb of charge passes a point in one second (1 coulomb equals the charge of 6.242 times 10^{18} electrons). Often the ampere is much too large a unit for measuring current. Therefore, the milliampere, one-thousandth of an ampere or the microampere (μA), one-millionth of an ampere, is used. The device that measures current is called an ammeter.

ELECTRICAL RESISTANCE

2-133. The directed movement of electrons constitutes a current flow. Electrons do not move freely through a conductor's crystalline structure. Some materials offer little opposition to current flow while other materials greatly oppose current flow. This opposition to current flow is resistance and the unit of measure is the ohm. The greater the resistance in the circuit the smaller the current will be from the power supply. Resistance is essential in a circuit. If all the resistance in a circuit were eliminated, a short circuit would result. If not prevented, this maximum current flow will damage the electrical system. The standard of measure for 1 ohm is the resistance provided at 0 degrees Celsius by a column of mercury having a cross-sectional area of 1 square millimeter and a length of 106.3 centimeters. A conductor has 1 ohm of resistance when an applied potential of 1 volt produces a current of 1 ampere. The symbol used to represent the ohm is the Greek letter omega (Ω).

2-134. Although an electrical property, resistance is determined by the physical structure of a material. Many of the same factors that control current flow govern the resistance of a material. Therefore, the factors that affect current flow will help explain the factors affecting resistance.

2-135. The magnitude of resistance is determined in part by the number of free electrons available within the material. Since a decrease in the number of free electrons will decrease the current flow, the opposition to current flow (resistance) is greater in a material with fewer free electrons. Therefore, the number of free electrons available in a material determines the resistance of a material. The conditions that limit current flow also affect resistance. The type of material, physical dimensions, and temperature affect the resistance of a conductor.

EFFECT OF TYPE OF MATERIAL

2-136. Depending on their atomic structure, different materials have different quantities of free electrons. Therefore, the various conductors used in electrical applications have different values of resistance.

2-137. Consider a simple metallic substance. Most metals are crystalline in structure and consist of atoms that are tightly bound in the lattice network. The atoms of such elements are so close together that the electrons in the outer shell of the atom are associated with one atom as much as with its neighbor (see Figure 2-27, view A). As a result, the force of attachment of an outer electron with an individual atom is practically zero. Depending on the metal, at least one electron, sometimes two, and, in a few cases, three electrons per atom exist in this state. In such cases, a relatively small amount of additional electron energy would free the outer electrons from the attraction of the nucleus. At normal room temperature, materials of this type have many free electrons and are good conductors. Good conductors have a low resistance.

2-138. If the atoms of a material are farther apart, the electrons in the outer shells will not be equally attached to several atoms as they orbit the nucleus (see Figure 2-27, view B). They are attracted to the nucleus of the parent atom only. Therefore, a greater amount of energy is required to free any of these electrons. Materials of this type are poor conductors and have a high resistance.

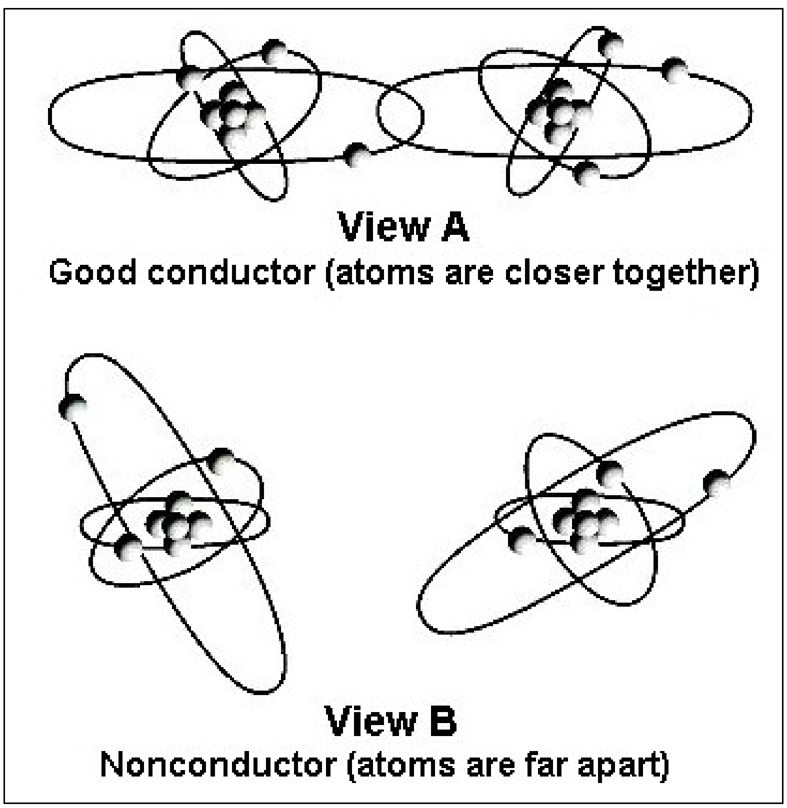

Figure 2-27. Atomic Spacing in Conductors

2-139. Silver, gold, and aluminum are good conductors. Therefore, materials composed of their atoms would have a low resistance. The element copper is the conductor most widely used throughout electrical applications. Silver has a lower resistance than copper, but its cost limits usage to circuits where a high conductivity is demanded. Aluminum, which is much lighter than copper, is used as a conductor when weight is a major factor.

EFFECT OF PHYSICAL DIMENSIONS

2-140. **Cross-sectional area**. Cross-sectional area greatly affects the magnitude of resistance. If the cross-sectional area of a conductor is increased, a greater quantity of electrons is available to move through the conductor. Therefore, a larger current will flow for a given amount of applied voltage. An increase in current indicates that when the cross-sectional area of a conductor is increased, the resistance must have decreased. If the cross-sectional area of a conductor is decreased, the number of available electrons decreases and, for a given applied voltage, the current through the conductor decreases. A decrease in current flow indicates that when the cross-sectional area of a conductor is decreased, the resistance must have increased. Therefore, the resistance of a conductor is inversely proportional to its cross-sectional area.

2-141. **Conductor diameter**. The diameter of conductors used in electronics is often only a fraction of an inch. Therefore, the diameter is expressed in mils (thousandths of an inch). It is also standard practice to assign the unit circular mil to the cross-sectional area of the conductor. The circular mil is found by squaring the diameter, when the diameter is expressed in mils. Therefore, if the diameter is 35 mils (0.035 inch) the circular mil area equals 35^2 or 1,225 circular mils. Figure 2-28 shows a comparison between a square mil and circular mil.

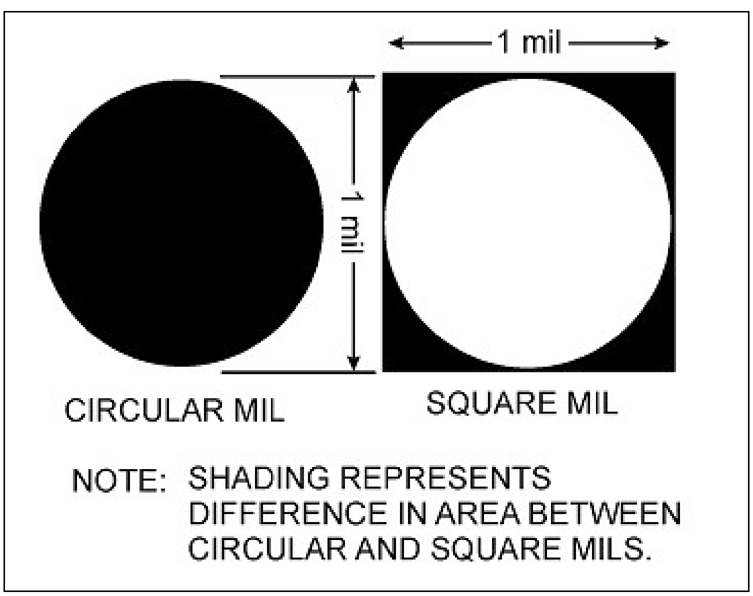

Figure 2-28. Square and Circular Mil

2-142. **Conductor length**. The length of a conductor is also a factor that determines the resistance of a conductor. If the length of a conductor is increased, the amount of energy given up increases. As free electrons move from atom to atom, some energy is given off as heat. The longer a conductor, the more energy is lost to heat. The additional energy loss subtracts from the energy being transferred through the conductor, resulting in a decrease in current flow for a given applied voltage. A decrease in current flow indicates an increase in resistance, because voltage was held constant. Therefore, if the length of a conductor is increased, the resistance increases. The resistance of a conductor is directly proportional to its length.

EFFECT OF TEMPERATURE

2-143. Temperature changes affect the resistance of materials in different ways. In some materials, an increase in temperature causes an increase in resistance. In others, an increase in temperature causes a decrease in resistance. The amount of change of resistance per unit change in temperature is the temperature coefficient. If for an increase in temperature the resistance of a material increases, it has a positive temperature coefficient. A material whose resistance decreases with an increase in temperature has a negative temperature coefficient. Most conductors used in electronic applications have a positive temperature coefficient. However, carbon (a frequently used material) is a substance with a negative temperature coefficient. Several materials (such as the alloys constantan and manganin) are considered to have a zero temperature coefficient because their resistance remains relatively constant for changes in temperature.

CONDUCTANCE

2-144. Electricity is often explained in terms of opposites. The opposite of resistance is conductance. Conductance is the ability of a material to pass electrons. The same factors that affect the magnitude of resistance affect conductance, but in the opposite manner. Conductance is directly proportional to area and inversely proportional to the length of the material. The temperature of the material is also a factor. With a constant temperature, the conductance of a material can be calculated.

2-145. The unit of conductance is the mho, which is ohm spelled backwards. Another term for mho is siemens. The relationship between R and G is a reciprocal one. A reciprocal of a number is 1 divided by the number. In terms of resistance and conductance—

$$R = \frac{1}{G}$$

$$G = \frac{1}{R}$$

ELECTRICAL RESISTORS

2-146. Resistance is a property of every electrical component. At times, its effects will be undesirable. However, resistance is used in many varied ways. Resistors are components manufactured in many types and sizes to possess specific values of resistance. In a schematic representation, a resistor is drawn as a series of jagged lines (see Figure 2-29).

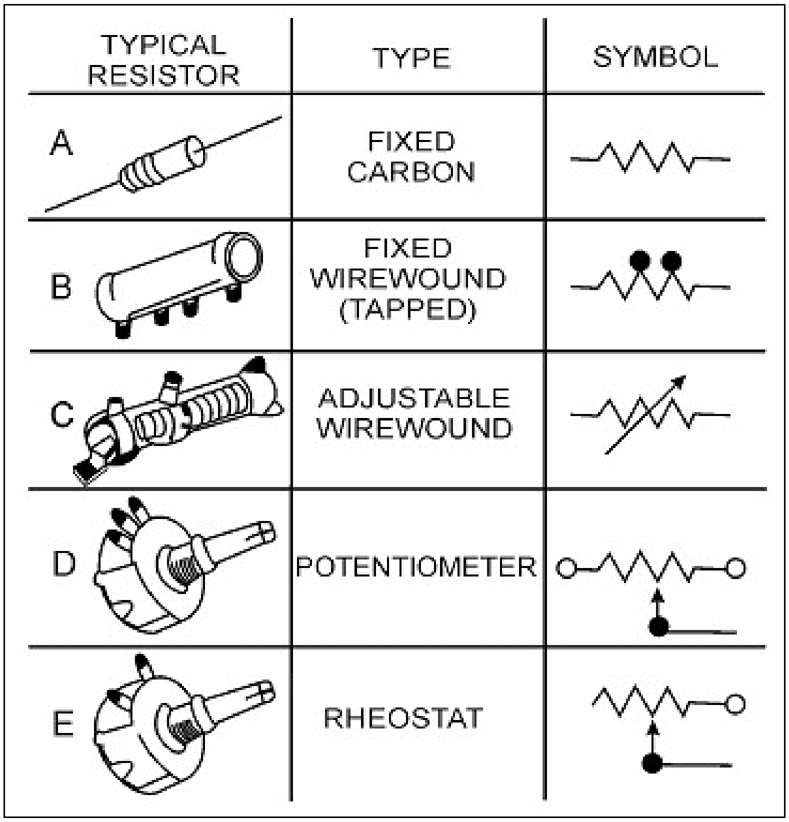

Figure 2-29. Types of Resistors

COMPOSITION OF RESISTORS

2-147. One of the most common types of resistors (usually referred to as the carbon resistor) is the molded composition. These resistors are manufactured in a variety of sizes and shapes. The chemical composition of the resistor, which is accurately controlled by the manufacturer, determines its ohmic value. Carbon resistors are made in ohmic values that range from 1 ohm to millions of ohms. The physical size of the resistor is related to its wattage rating. This rating measures the resistor's ability to dissipate heat caused by the resistance.

2-148. Carbon is the main ingredient of carbon resistors. In their manufacture, fillers or binders are added to the carbon to obtain various resistor values. Examples of these fillers are clay, bakelite, rubber, and talc. These fillers are doping agents that change the overall conduction characteristics. Carbon resistors are the most common resistors because they are inexpensive and easy to manufacture. They also have an adequate tolerance for most electrical and electronic applications. Their prime disadvantage is that they tend to change value as they age. Another disadvantage is their limited power-handling capacity.

2-149. The disadvantage of carbon resistors can be overcome by using wirewound resistors (see Figure 2-29, views B and C). These resistors have very accurate values and can handle higher current than carbon resistors. The material often used to manufacture wirewound resistors is German silver. German silver is composed of copper, nickel, and zinc. The qualities and quantities of these elements in the wire determine the resistivity of the wire, which is the measure or ability of the wire to resist current. Usually the percent of nickel in the wire determines the resistivity. One disadvantage of the wirewound resistor is that it takes a large amount of wire to manufacture a resistor of high ohmic value, thereby increasing the cost.

2-150. A variation of the wirewound resistor provides an exposed surface to the resistance wire on one side. An adjustable tap is attached to this side. Such resistors, sometimes with two or more adjustable taps, are used as voltage dividers in power supplies and in other applications where a specific voltage needs to be tapped off.

TYPES OF RESISTORS

2-151. The two kinds of resistors are freed and variable. The freed resistor has one value and never changes, except through the effects of temperature, age, and so forth. The resistors in Figure 2-29, views A and B, are fixed resistors. The tapped resistor in view B has several fixed taps, which makes more than one resistance value available. The resistor in view C has an adjustable collar that can be moved to tap off any resistance within the ohmic value range of the resistor.

2-152. The two types of variable resistors are the potentiometer and the rheostat (see Figure 2-29, views D and E). An example of the potentiometer is the volume control on your radio. An example of the rheostat is the dimmer control for the dash lights in an automobile. However, there is a slight difference between them. Rheostats usually have two connections (one fixed and the other movable). Any variable resistor can properly be called a rheostat. The potentiometer always has three connections (two fixed and one movable). Generally, the rheostat has a limited range of values and high current-handling capability. The potentiometer has a wide range of values, but it usually has a limited current-handling capability. Potentiometers are always connected as voltage dividers.

WATTAGE RATING

2-153. When a current is passed through a resistor, heat develops within the resistor. The resistor must be able to dissipate this heat into the surrounding air. Otherwise, the temperature of the resistor rises, producing a change in resistance or possibly causing the resistor to burn out.

2-154. The resistor’s ability to dissipate heat depends on the design of the resistor (such as, on the amount of surface area exposed to the air). Therefore, a resistor designed to dissipate a large amount of heat must be large. The heat dissipating capability of a resistor is measured in watts.

Some of the more common wattage ratings of carbon resistors are 1/8 watt, 1/4 watt, 1/2 watt, 1 watt, and 2 watts. In some of the newer state-of-the-art circuits, much smaller wattage resistors are used. Generally, the types that can be physically worked with are of the values above. The higher the wattage rating of the resistor, the larger its physical size. Resistors that dissipate very large amounts of power (watts) are usually wirewound resistors. Wirewound resistors with wattage ratings up to 50 watts are not uncommon. Figure 2-30 shows some resistors with different wattage ratings.

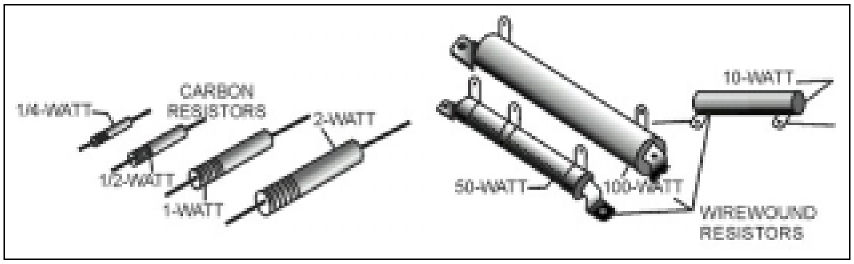

Figure 2-30. Resistors of Different Wattage Ratings

STANDARD COLOR CODE SYSTEM

2-155. In the standard color code system, four bands are painted on the resistor (see Figure 2-31). The following describes the color of each band:

- The first band shows the value of the first significant digit.
- The second band shows the value of the second significant digit.
- The third band represents a decimal multiplier by which the first two digits must be multiplied to obtain the resistance value of the resistor.
- The fourth band represents the tolerance.

The colors for the bands and their corresponding values are shown in Table 1-1.

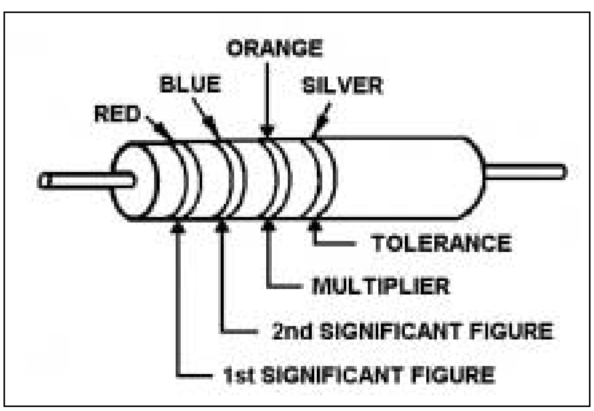

Figure 2-31. Resistor Color Codes

Table 2-1. Standard Color Code for Resistors

Color	Significant Figure	Decimal Multiplier	Resistance Tolerance	Reliability Level Per 1000 Hours
BLACK	0	1	PERCENT ±	
BROWN	1	10	---	1%
RED	2	100	---	.1%
ORANGE	3	1,000	---	.01%
YELLOW	4	10,000	---	.001%
GREEN	5	100,000	---	
BLUE	6	1,000,000	---	
VIOLET	7	10,000,000	---	
GRAY	8	100,000,000	---	
WHITE	9	1,000,000,000	---	
GOLD	---	.1	5	
SILVER	---	.01	10	
NO COLOR	---		20	

2-156. Use the example colors shown in Figure 2-31. Since red is the color of the first band, the first significant digit is 2. The second band is blue; therefore, the second significant digit is 6. The third band is orange, which shows that the number formed as a result of reading the first two bands is multiplied by 1,000. In this case, 26 x 1,000 = 26,000 ohms. The last band on the resistor shows the tolerance. Tolerance is the manufacturer's allowable deviation from the numerical value given on the resistor. In this instance, its color is silver and the tolerance is 10 percent plus or minus of the value of the resistor. The allowed limit of variation is the ohmic value of this particular resistor is 23,4000 to 28,600 ohms.

2-157. When measuring resistors, you will find situations in which the quantities to be measured may be extremely large. You will also find that the resulting number using the basic unit (the ohm) may prove too cumbersome. Therefore, a metric system prefix is usually attached to the basic unit of measurement to provide a more manageable unit. Two of the most commonly used prefixes are kilo and mega. Kilo is the prefix used to represent thousand and is abbreviated “k”. Mega is the prefix used to represent million and is abbreviated “M”.

2-158. In the example given above, the 26,000-ohm resistor could have been written as 26 kilohms or 26kΩ. Other examples include:

- 1,000 ohms = 1kΩ.
- 10,000 ohms = 10kΩ.
- 100,000 ohms = 100kΩ.

Also, 1,000,000 ohms is written as 1 megohm or 1MΩ and 10,000,000 ohms = 10MΩ.

SIMPLYING THE COLOR CODE

2-159. Resistors are the most common components used in electronics. The technician must identify, select, check, remove, and replace resistors. Resistors and resistor circuits are usually the easiest branches of electronics to understand.

2-160. The resistor color code sometimes presents problems to a technician. However, once you learn the resistor color code you should remember it for the rest of your life. The colors you should know automatically are as follows:

- Black.
- Brown.
- Red.
- Orange.
- Yellow.
- Green.
- Blue.
- Violet.
- Gray.
- White.

There is a memory aid that will help you remember the code in its proper order. Each word starts with the first letter of the colors. If you match it up with the color code, you will not forget the code. The memory aid is an acrostic which reads “Bad Boys Run Over Yellow Gardenias Behind Victory Garden Walls” or—

- Black – Bad
- Brown – Boys
- Red – Run
- Orange – Over
- Yellow – Yellow
- Green – Gardenias
- Blue – Behind
- Violet – Victory
- Gray – Garden
- White – Walls

2-161. There are many other memory aid sentences that you might want to ask about from experienced technicians or come up with yourself. You might find one of the other sentences easier to remember.

2-162. There is still a good chance that you will make a mistake on a resistor's color band. Most technicians do at one time or another. If you make a mistake on the first two significant colors, it usually is not too serious. However, if you make a mistake on the third band there is trouble because the value is going to be at least 10 times too high or too low. The following are some important points to remember about the third band. When the third band is—

- Black, the resistor must be less than 100 ohms.
- Red, the resistor must be in hundreds of ohms.
- Orange, the resistor must be in thousands of ohms.
- Yellow, the resistor must be in hundreds of thousands of ohms.
- Green, the resistor must be in megohms.
- Blue, the resistor must be in tens of megohms or more.

Red, orange, and yellow are the most common colors for the third band. Remembering these colors can avoid a lot of trouble when selecting resistors from a parts bin.

2-163. The fourth band, which is the tolerance band, usually does not present too much of a problem. If there is no fourth band, it means that the resistor has a 20 percent tolerance. A resistor with a silver fourth band means a resistor has a 10 percent tolerance. A resistor with a gold fourth band means a resistor has a 5 percent tolerance. In some cases, the third band will be silver or gold. It then becomes a multiplier. That means, you multiply the first two bands by 0.01 if it is silver and 0.1 if it is gold. Resistors that conform to military specifications have an additional fifth band. The fifth band shows the reliability level per 1,000 hours. For example; if the fifth band color is brown, the reliability level would be 1.0 percent. If the fifth band color is red, the reliability level would be 0.1 percent. If the fifth band color is orange, the reliability level would be 0.01 percent. If the fifth band color is yellow, the reliability level would be 0.001 percent.

2-164. In applying the reliability level table for a resistor color coded brown, the chance of failure will not exceed 1 percent for every 1,000 hours of operation of that resistor. In equipment such as the Navy's complex computers this is very significant. In a piece of equipment containing 10,000 orange fifth-band resistors, it means that no more than one resistor will fail during 1,000 hours of operation.

2-165. Some resistors (both wirewound and composition) will not use the resistor color code. These resistors will have the ohmic value and tolerance imprinted on the resistor itself.

FUNDAMENTALS OF ELECTRICITY

Questions

1. What is matter and in what three states is it found?
2. What is an element?
3. What is a compound?
4. What is a mixture?
5. What is an atom?
6. How are elements classified?
7. What two types of energy does an electron contain?
8. What is the difference between the chemical activity and stability of atoms?
9. What is the name given to the outermost shell of the atom?
10. What is the name of the process where an atom loses or gains electrons?
11. What metal is the best conductor?
12. What do you call materials that are neither good conductors nor good insulators?
13. What is the easiest way to create a static charge?
14. What determines the charge of a substance?
15. What is the fundamental law of electricity?
16. What is an electric field of force?
17. In what direction are electrostatic lines of force drawn?
18. What is the difference between a permanent magnet and a temporary magnet?
19. How is the law of magnetic poles?
20. What determines the effectiveness of the magnetic field of an atom?
21. What is the name of the space around a magnet where magnetic forces act?
22. What are magnetic lines of force?
23. In what direction to magnetic lines of force travel inside a magnet?
24. What should you use to direct magnetic flux around sensitive mechanisms and electric instruments and meters?
25. What are the three classifications of magnets?
26. What is the definition of energy?
27. What is the name of energy contained in an object because of its position?
28. What term describes voltage or EMF?
29. What is the fundamental law of electricity?
30. What is a voltage source?
31. Presently there are how many methods for producing a voltage or EMF?
32. The thermoelectric voltage in a thermocouple depends mainly on what?

FUNDAMENTALS OF ELECTRICITY

Questions

33. What photosensitive materials are most commonly used to produce photoelectric voltage?
34. What are the two types of primary cells?
35. What is the most useful and widely employed application of magnets?
36. Is random drift greater in a conductor or an insulator?
37. On what does the magnitude of current flow mainly depend?
38. In what is the magnitude of current is measured?
39. How is resistance determined?
40. What refers to the amount of change of resistance per unit change in temperature?
41. What is the unit of conductance?
42. What are the most common used resistors?
43. What are the two kinds of resistors?
44. What are the two types of variable resistors?
45. How many bands are on a resistor in the standard color code system?
46. What are the most common components used in electronics?

Chapter 3

Direct Current

This chapter describes the basic DC circuit and the basic schematic diagram of that circuit. The schematic diagram is used when working in electricity and electronics. This chapter also describes the series DC circuit and the parallel DC circuit. It explains how to determine the total resistance, current, voltage, and power in a series, parallel, or series-parallel network through the use of Ohm's and Kirchhoff's laws.

BASIC ELECTRIC CIRCUIT

3-1. An electric circuit is a closed loop path consisting of a source, a load, and a switch. A flashlight is an example of a basic electric circuit. A flashlight contains the following:

- A source of electrical energy (the dry cells in the flashlight).
- A load (the bulb) that changes the electrical energy into a more useful form of energy (light).
- A switch to control the energy delivered to the load.

3-2. A load is any device through which an electrical current flows and that changes this electrical energy into a more useful form. The following are common examples of loads:

- A light bulb (changes electrical energy into light energy).
- An electric motor (changes electrical energy into mechanical energy).
- A speaker in a radio (changes electrical energy into sound).

A source is the device that furnishes the electrical energy used by the load. It may be a simple dry cell (as in a flashlight), a storage battery (as in an automobile), or a power supply (such as a battery charger). A switch permits control of the electrical device by interrupting the current delivered to the load.

SCHEMATIC DIAGRAMS

3-3. A schematic diagram is a drawing of a circuit that uses symbols to represent the various circuit components. It is the engineer's main aid in troubleshooting a circuit. A relatively small diagram can show large or complex circuits. Schematic symbols are used throughout the study of electricity and electronics.

3-4. The schematic diagram in Figure 3-1 represents a flashlight. In the de-energized state (view A), the switch (S1) is open. There is not a complete path for current (I) through the circuit, so the bulb (DS1) does not light. In the energized state (view B), the switch (S1) is closed.

Current flows from the negative terminal of the battery (BAT), through the switch (S1) through the lamp (DS1), and back to the positive terminal of the battery. With the switch closed, the path for current is complete. Current will continue to flow until the switch (S1) is moved to the open position or the battery is completely discharged.

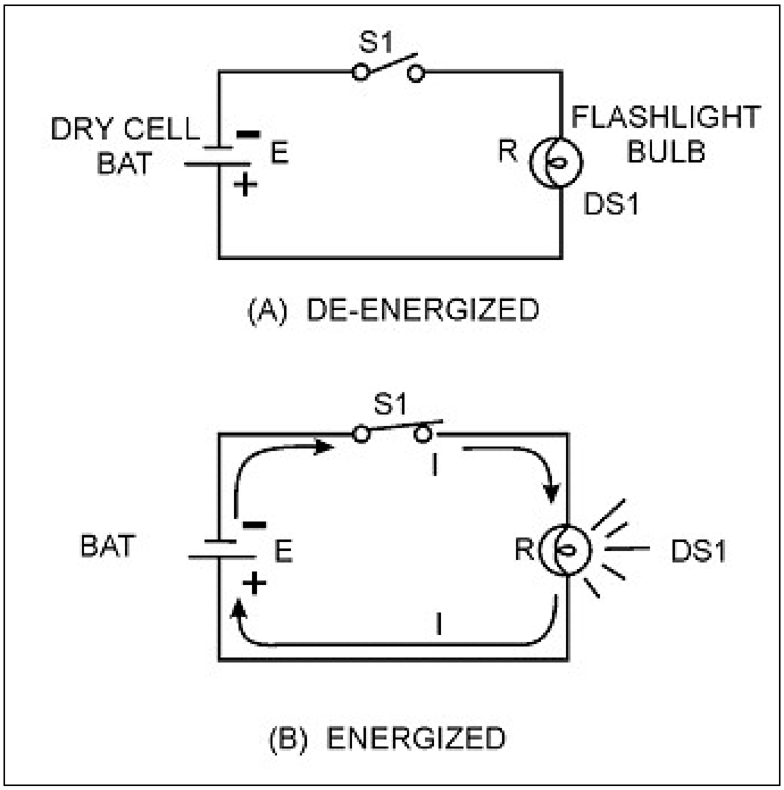

Figure 3-1. Flashlight Schematic

OHM'S LAW

3-5. In the early part of the 19th century, George Simon Ohm proved by experiment that a precise relationship exists between current, voltage, and resistance. This relationship, called Ohm's law, is stated as follows:

"The current in a circuit is directly proportional to the applied voltage and inversely proportional to the circuit resistance."

Ohm's law may be expressed as an equation.

$$I = \frac{E}{R}$$

Where:

I =	current in amperes
E =	voltage in volts
R =	resistance in ohms

3-6. As stated in Ohm's law, current is inversely proportional to resistance. As the resistance in a circuit increases, the current decreases proportionately.

3-7. In the equation I = E/R, if any two quantities are known, you can determine the third one. Refer to Figure 3-1, view B, which is the schematic representation of a flashlight. If the battery (BAT) supplies a voltage of 1.5 volts and the lamp (DS1) has a resistance of 5 ohms, then you can determine the current in the circuit by substituting these values in the equation:

Given:

E = 1.5 volts

R = 5 ohms

Solution:

$$I = \frac{E}{R} = \frac{1.5 \text{ volts}}{5 \text{ ohms}} = .3 \text{ ampere}$$

3-8. If the flashlight were a two-cell flashlight, twice the voltage (or 3.0 volts) would be applied to the circuit. You can determine the current in the circuit using this voltage in the equation:

Given:

E = 3.0 volts

R = 5 ohms

Solution:

$$I = \frac{E}{R} = \frac{3.0 \text{ volts}}{5 \text{ ohms}} = .6 \text{ ampere}$$

As the applied voltage is doubled, the current flowing through the circuit also doubles. This shows that the current is directly proportional to the applied voltage.

3-9. If the value of resistance of the lamp is doubled, you can determine the current in the circuit by the following equation:

Given:

E = 3.0 volts

R = 10 ohms

Solution:

$$I = \frac{E}{R} = \frac{3.0 \text{ volts}}{10 \text{ ohms}} = .3 \text{ ampere}$$

The current has been reduced to one-half of the value of the previous equation, or .3 ampere. This shows that the current is inversely proportional to the resistance. Therefore, doubling the value of the resistance of the load reduces the circuit current value to one-half of its former value.

3-10. Figure 3-2 and Figure 3-3 are diagrams for determining resistance and voltage in a basic circuit, respectively.

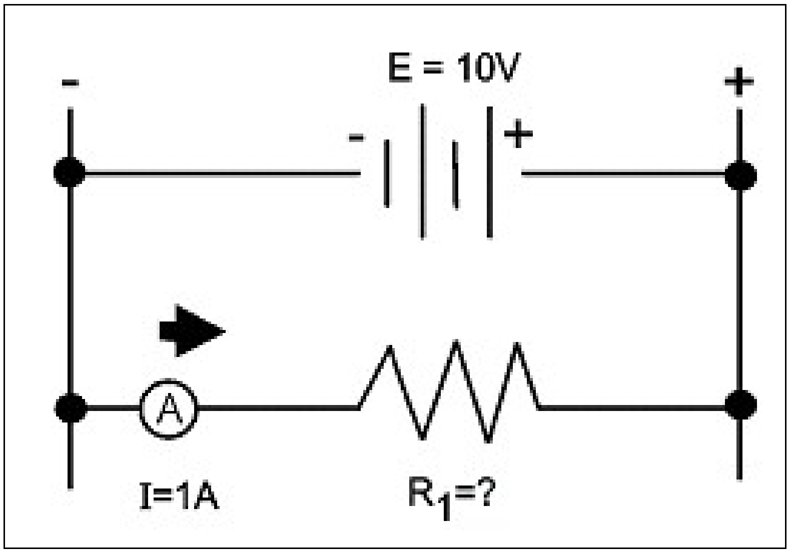

Figure 3-2. Determining Resistance in a Basic Circuit

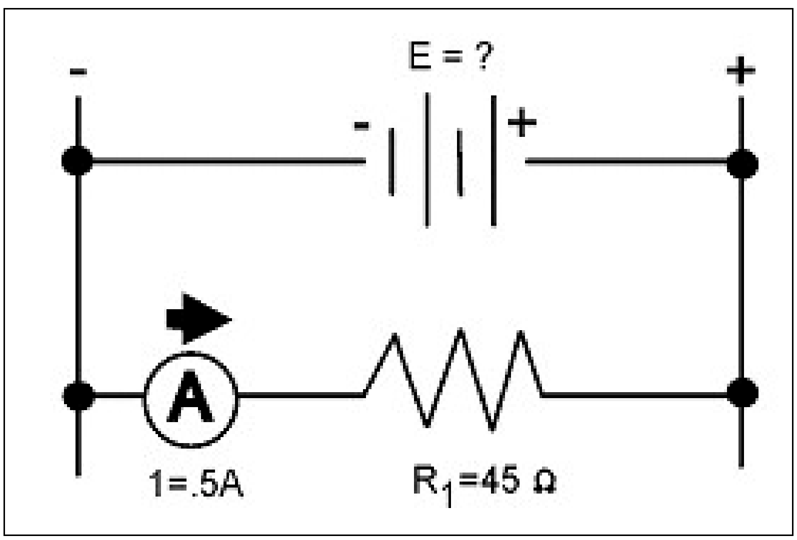

Figure 3-3. Determining Voltage in a Basic Circuit

3-11. Using Ohm's law, the resistance of a circuit can be determined if only the voltage and the current in the circuit are known. In any equation, if all the variables (parameters) are known except one, that unknown can be found. For example, using Ohm's law, if current (I) and voltage (E) are known, you can determine resistance (R), the only parameter not known. The basic formula is as follows:

$$I = \frac{E}{R}$$

This formula may also be expressed as—

$$E = I \times R$$

Or:

$$R = \frac{E}{I}$$

3-12. The Ohm's law equation and its various forms may be obtained readily using the diagrams in Figure 3-4. The circle containing E, I, and R at the bottom of the figure is divided into two parts, with E above the line and I and R below the line. To determine the unknown quantity, first cover that quantity with a finger. The position of the uncovered letters in the circle will indicate the mathematical operation to be performed.

3-13. For example, to find I, cover I with a finger. The uncovered letters indicate that E is to be divided by R, or—

$$I = \frac{E}{R}$$

3-14. To find the formula for E, cover E with your finger. The result indicates that I is to be multiplied by R, or—

$$E = IR$$

3-15. To find the formula for R, cover R. The result indicates that E is to be divided by I, or—

$$R = \frac{E}{I}$$

POWER

3-16. Power, whether electrical or mechanical, pertains to the rate at which work is being done. Work is done whenever a force causes motion. When a mechanical force is used to lift or move a weight, work is done. However, force exerted without causing motion (such as the force of a compressed spring acting between two freed objects) does not constitute work.

3-17. Voltage is an electrical force that forces current to flow in a closed circuit. However, when voltage exists but current does not flow because the circuit is open, no work is done. This is similar to the spring under tension that produced no motion. The instantaneous rate at which this work is done is called the electric power rate and is measured in watts.

3-18. A total amount of work may be done in different lengths of time. For example, a given number of electrons may be moved from one point to another in 1 second or in 1 hour, depending on the rate at which they are moved. In both cases, total work done is the same. However, when the work is done in a short time, the wattage, or instantaneous power rate, is greater than when the same amount of work is done over a longer period of time.

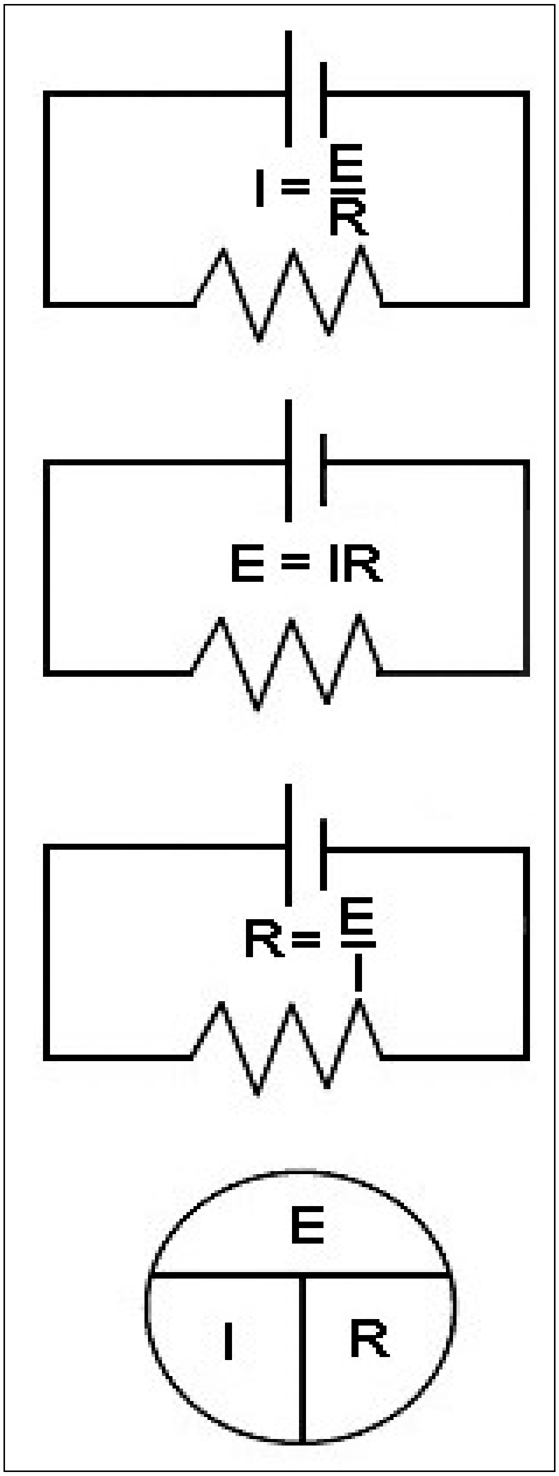

Figure 3-4. Ohm's Law in Diagram Form

3-19. The basic unit of power is the watt. Power in watts equals the voltage across a circuit multiplied by current through the circuit. This represents the rate at any given instant at which work is being done. The symbol P indicates electrical power. The following is the basic power formula:

P = I x E

Where:

P =	power (in watt-hours)
I =	current in the circuit
E =	voltage

The amount of power changes when either voltage or current, or both, are changed.

3-20. In practice, the only factors that can be changed are voltage and resistance. In explaining the different forms that formulas may take, current is sometimes presented as a quantity that is changed. Remember, if current is changed it is because either voltage or resistance has been changed.

3-21. Four of the most important electrical quantities are voltage (E), current (I), resistance (R), and power (P). The relationships among these quantities are used throughout the study of electricity. Previously, P was expressed in terms of alternate pairs of the other three basic quantities (E, I, and R). In practice, any one of these quantities can be expressed in terms of any two of the others.

3-22. Figure 3-5 is a summary of 12 basic formulas. The four quantities (E, I, R, and P) are at the center of the figure. Next to each quantity are three segments. In each segment, the basic quantity is expressed in terms of two other basic quantities. No two segments are alike.

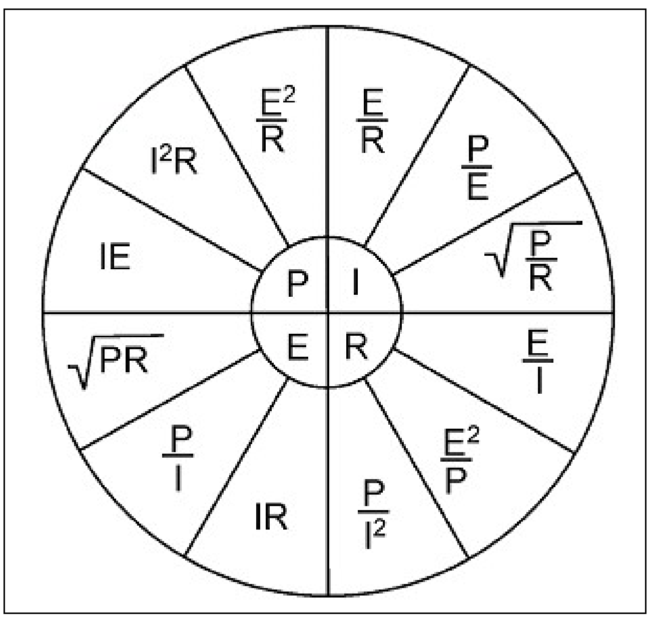

Figure 3-5. Summary of Basic Formulas

3-23. For example, you can use the formula wheel in Figure 3-5 to find the formula to solve this problem. A circuit has a source voltage of 24 volts and a measured current of 10 amperes. To compute the power rate, find P in the center of the wheel. I x E, or current multiplied by voltage, fits the supplied information.

Given:

I =	10 amps
E =	24 volts

Solution:

P =	I x E
P =	10 x 24
P =	240 watts

POWER RATING

3-24. Electrical components are often given a power rating. The power rating, in watts, indicates the rate at which the device converts electrical energy into another form of energy (such as light, heat, or motion). For example, a 150-watt lamp can convert more electrical energy into light energy than a 100-watt lamp. Other common examples of devices with power ratings are soldering irons and small electric motors.

3-25. In some electrical devices, the wattage rating indicates the maximum power the device is designed to use rather than the normal operating power. For example, a 150-watt lamp uses 150 watts when operated at the specified voltage printed on the bulb. In contrast, a device (such as a resistor) is not normally given a voltage or a current rating. A resistor is given a power rating in watts and can be operated at any combination of voltage and current as long as the power rating is not exceeded. In most circuits, the actual power a resistor uses is considerably less than the power rating of the resistor because a 50 percent safety factor is used. For example, if a resistor normally used 2 watts of power, a resistor with a power rating of 3 watts would be selected.

3-26. Resistors of the same resistance value are available in different wattage values. For example, carbon resistors are commonly made in wattage ratings of 1/8, 1/4, l/2, 1, and 2 watts. The larger the physical size of a carbon resistor, the higher the wattage rating. This is true because a larger surface area of material radiates a greater amount of heat more easily.

3-27. Wirewound resistors are used when resistors with wattage ratings greater than 5 watts are needed. Wirewound resistors are made in values between 5 and 200 watts, with special types being used for power in excess of 200 watts.

3-28. As with other electrical quantities, prefixes may be attached to the word “watt” when expressing very large or very small amounts of power. Some of the more common are the megawatt (1,000,000 watts), the kilowatt (1,000 watts), and the milliwatt (1/1,000 of a watt).

POWER CONVERSION AND EFFICIENCY

3-29. The term “power consumption” is common in the electrical field. It is applied to the use of power in the same sense that gasoline consumption is applied to the use of fuel in an automobile.

3-30. Another common term is “power conversion.” Power used by electrical devices is converted from one form of energy to another. An electrical motor converts electrical energy to mechanical energy. An electric light bulb converts electrical energy into light energy and an electric range converts electrical energy into heat energy. The power electrical devices use is measured in watt-hours. This practical unit of electrical energy equals 1 watt of power used continuously for 1 hour. The term “kilowatt hour”, used more often on a daily basis, equals 1,000 watt-hours.

3-31. The EFF of an electrical device is the ratio of power converted to useful energy divided by the power consumed by the device. This number will always be less than one (1.00) because of the losses in any electrical device. If a device has an efficiency rating of .95, it effectively transforms 95 watts into useful energy for every 100 watts of input power. The other 5 watts are lost to heat or other losses that cannot be used.

3-32. To calculate the amount of power converted by an electrical device is simple. The length of time the device is operated and the input power in horsepower rating are needed (1 horsepower equals 746 watts). Horsepower, a unit of work, is often found as a rating on electrical motors.

Example: A 3/4-HP motor operates 8 hours a day. Use the following equation to compute how much power is converted by the motor per month and how many kWh it represents.

Equation:

P = work x watts x hours

Given:

time =	8 hours per day x 30 days = 240
P =	3/4 HP
1 HP =	746 watts

Solution:
First, knowing that 1HP = 746 watts, convert horsepower to watts—

P =	3/4 x 746 watts
P =	559 watts

Then, use the following to convert watts to watt-hours—

$$P = 559 \text{ watts} \times 240 \text{ hours}$$

$$P = 134{,}000 \text{ watt-hours per month}$$

Note: These figures are approximate.

Use the following to convert the power in watt-hours to kWh:

$$P = \frac{\text{Power in watt-hours}}{1{,}000}$$

$$P = \frac{134{,}000 \text{ watt-hours}}{1{,}000}$$

$$P = 134 \text{ kWh}$$

3-33. Using the above example, if the motor actually uses 137 kWh per month, use the following to determine the efficiency of the motor:

Equation:

$$\mathbf{EFF} = \frac{\textbf{Power converted}}{\textbf{Power used}}$$

Given:

Power converted = 134 kWh per month

Power used = 137 kWh per month

Solution:

$$EFF = \frac{134 \text{ kWh per month}}{137 \text{ kWh per month}}$$

$$EFF = .978 \text{ (rounded to three figures)}$$

SERIES DIRECT CURRENT CIRCUITS

3-34. When a conductor connects two unequal charges, a complete pathway for current exists. An electric circuit is a complete conducting pathway. It consists of the conductor and the path through the voltage source. Inside the voltage source, current flows from the positive terminal, through the source, and emerges at the negative terminal.

CHARACTERISTICS

3-35. A series circuit is a circuit that contains only one path for current flow. Figure 3-6 shows the basic circuit and a more complex series circuit. The basic circuit has only one lamp and the series circuit has three lamps connected in series.

3-36. **Resistance in a series circuit**. The current in a series circuit must flow through each lamp to complete the electrical path in the circuit (see Figure 3-6). Each additional lamp offers added resistance. In a series circuit, the total circuit resistance (R_T) equals the sum of the individual resistances ($R_T = R_1 + R_2 + R_3 + \ldots R_n$).

Note: The subscript "n" denotes any number of additional resistances that might be in the equation.

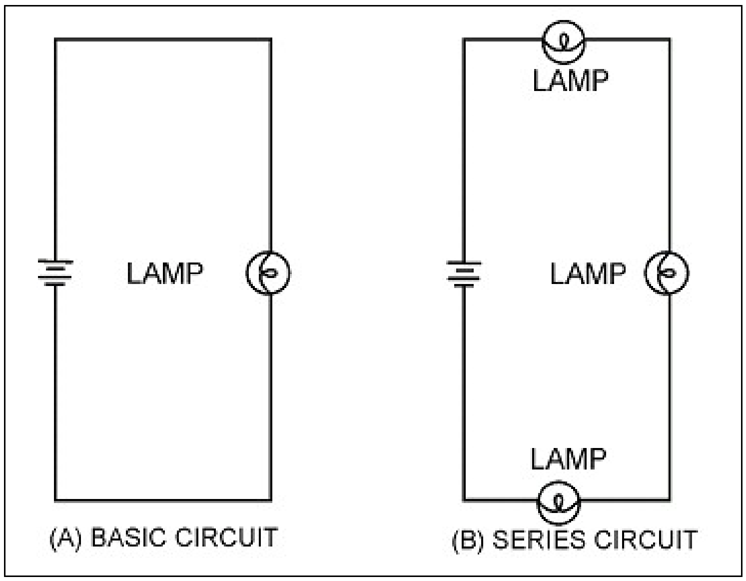

Figure 3-6. Comparison of Basic and Series Circuits

Example: Figure 3-7 shows a series circuit consisting of three resistors (10 ohms, 15 ohms, and 30 ohms). Use the following equation to determine what is the total resistance.

Equation:

$$\mathbf{R_T = R_1 + R_2 + R_3}$$

Given:

R_1 =	10 ohms
R_2 =	15 ohms
R_3 =	30 ohms

Solution:

R_T =	$R_1 + R_2 + R_3$
R_T =	10 ohms + 15 ohms + 30 ohms
R_T =	55 ohms

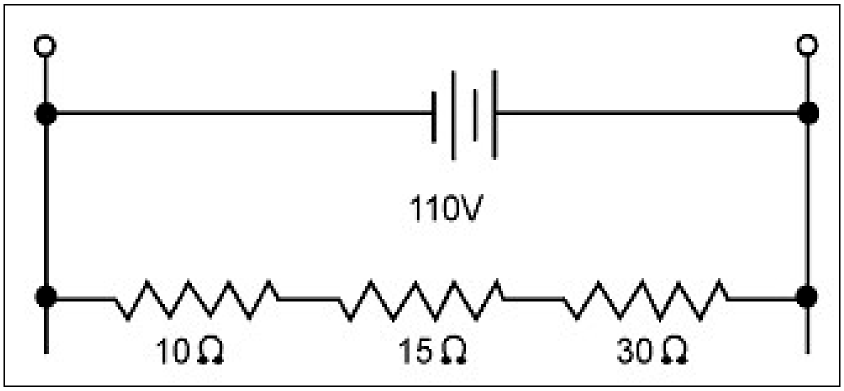

Figure 3-7. Calculating Total Resistance in a Series Circuit

3-37. In some circuit applications, the total resistance is known and the value of one of the circuit resistors has to be determined. The equation $R_T = R_1 + R_2 + R_3$ can be transposed to solve for the value of the unknown resistance (see Figure 3-8).

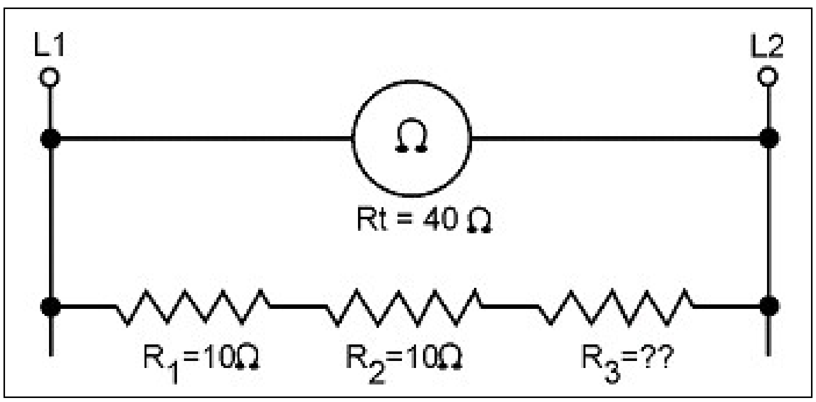

Figure 3-8. Calculating the Value of One Resistance in a Series Circuit

Equation:

$$\mathbf{R_3 = R_T + R_1 + R_2}$$

Given:

R_T =	40 ohms
R_1 =	10 ohms
R_2 =	10 ohms

Solution:

R_3 =	$R_T - R_1 - R_2$
R_3 =	40 ohms – 10 ohms – 10 ohms
R_3 =	20 ohms

3-38. **Current in a series circuit**. Since there is only one path for current in a series circuit, the same current must flow through each component of the circuit. Only the current through one of the components needs to be known to determine the current in a series circuit.

3-39. You can verify that the same current flows through each component of a series circuit by inserting meters into the circuit at various points (see Figure 3-9). When this is done, each meter will indicate the same value of current.

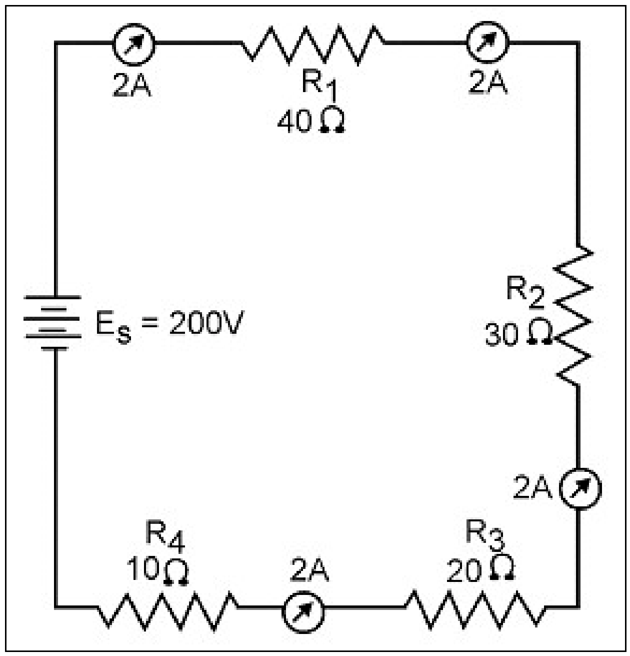

Figure 3-9. Current in a Series Circuit

3-40. **Voltage in a series circuit**. The loads in a circuit consume voltage (energy). This is called a voltage drop. Voltage drop across the resistor in a circuit consisting of a single resistor and a voltage source is the total voltage across the circuit and equals the applied voltage. The total voltage across a series circuit that consists of more than one resistor is also equal to the applied voltage but consists of the sum of the individual resistor voltage drops. In any series circuit, the sum of the resistor voltage drops must equal the source voltage. An examination of the circuit in Figure 3-10 demonstrates this point. In the figure, a source potential (E_T) of 20 volts is consumed by a series circuit consisting of two 5-ohm resistors. The total resistance of the circuit (R_T) equals the sum of the two individual resistances or 10 ohms. Using Ohm's law, one can calculate the circuit current (I) as shown in the following:

Equation:

$$I_T = \frac{E_T}{R_T}$$

Given:

E_T = 20 volts

R_T = 10 ohms

Solution:

$I_T = \frac{E_T}{R_T}$

$I_T = \frac{20 \text{ volts}}{10 \text{ ohms}}$

I_T = 2 amps

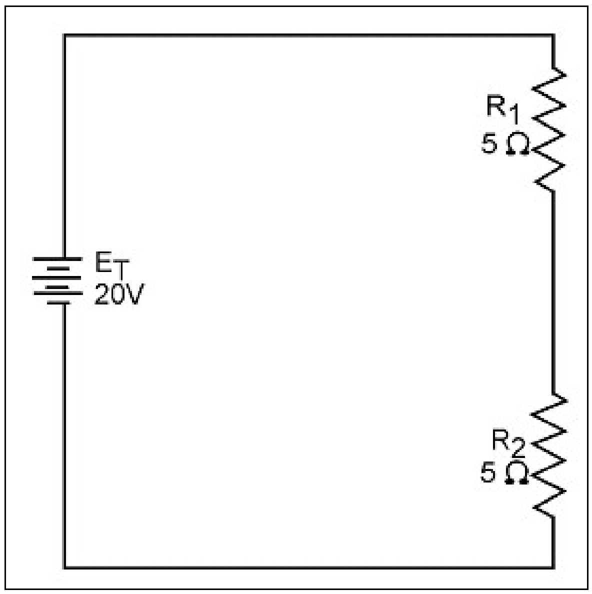

Figure 3-10. Calculating Individual Voltage Drops in a Series Circuit

3-41. The value of the resistors in Figure 3-10 is 5 ohms each and the current through the resistors is 2 amperes. With these values known, you can calculate the voltage drops across the resistors. Calculate the voltage (E_l) across R_1 as follows:

Equation:

$$\mathbf{E_1 = I_1 \times R_1}$$

Given:

I_1 = 2 amps

R_1 = 5 ohms

Solution:

E_1 = $I_1 \times R_1$

E_1 = 2 amps x 5 ohms

E_1 = 10 volts

3-42. R_2 is the same ohmic value as R_1 and carries the same current. Therefore, the voltage drop across R_2 is also equal to 10 volts. Adding these two 10-volt drops together gives a total drop of 20 volts, equal to the applied voltage. For series circuit, then—

$$E_T = E_1 + E_2 + E_3 + \ldots E_n$$

Example: A series circuit consists of three resistors having values of 20 ohms, 30 ohms, and 50 ohms, respectively. Find the applied voltage if the current through the 30-ohm resistor is 2 amperes. To solve the problem, first draw and label a circuit diagram as shown in Figure 3-11.

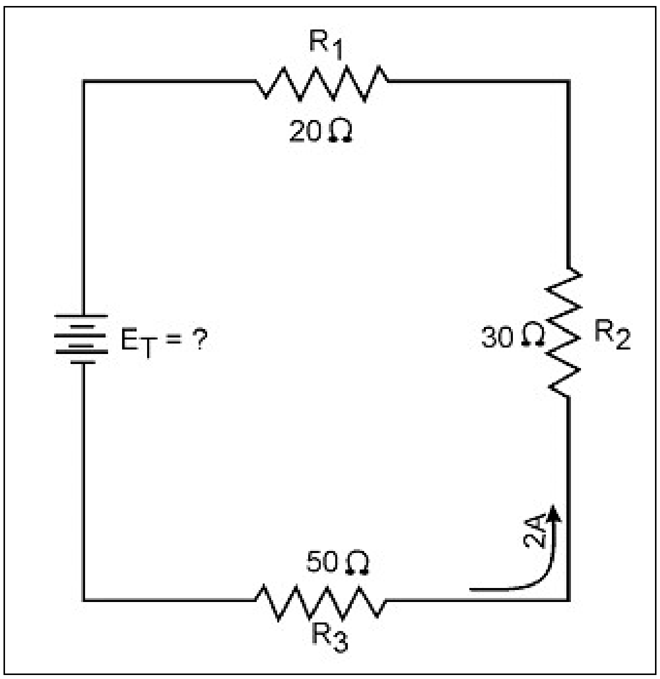

Figure 3-11. Calculating Applied Voltage in a Series Circuit

Equations:

E_T =	$E_1 + E_2 + E_3$
E_1 =	$R_1 \times I_1$ (I_1 = the current through resistor R_1)
E_2 =	$R_2 \times I_2$
E_3 =	$R_3 \times I_3$

Given:

R_1 = 20 ohms

R_2 = 30 ohms

R_3 = 50 ohms

I = 2 amps

Solution:

$E_T = E_1 + E_2 + E_3$

$E_1 = R_1 \times I_1$ (I_1 = the current through resistor R_1)

$E_2 = R_2 \times I_2$

$E_3 = R_3 \times I_3$

Substituting—

$E_T = (R_1 \times I_1) + (R_2 \times I_2) + (R_3 \times I_3)$

E_T = (20 ohms x 2 amps) + (30 ohms x 2 amps) + (50 ohms x 2 amps)

E_T = 40 volts + 60 volts + 100 volts

E_T = 200 volts

Note: When you use Ohm's law, the quantities for the equation must be taken from the same part of the circuit. In the above example, the voltage across R_2 was computed using the current through R_2 and the resistance of R_2.

3-43. The applied voltage determines the value of the voltage dropped by a resistor. It is in proportion to the circuit resistances. The voltage drops that occur in a series circuit are in direct proportion to the resistances. This is the result of having the same current flow through each resistor. The larger the ohmic value of the resistor, the larger the voltage drop across it.

3-44. **Power in a series circuit**. Each of the loads in a series circuit consumes power that is dissipated in the form of heat. Since this power must come from the source, the total power supplied must be equal to the power consumed by the circuit's loads. In a series circuit, the total power equals the sum of the power dissipated by the individual loads. Total power (P_T) equals—

$$P_T = P_1 + P_2 + P_3 + \ldots P_n$$

Example: A series circuit consists of three resistors having values of 5 ohms, 10 ohms, and 15 ohms. Find the total power when 120 volts is applied to the circuit (see Figure 3-12). Remember, the total power equals the sum of the power used by the individual resistors.

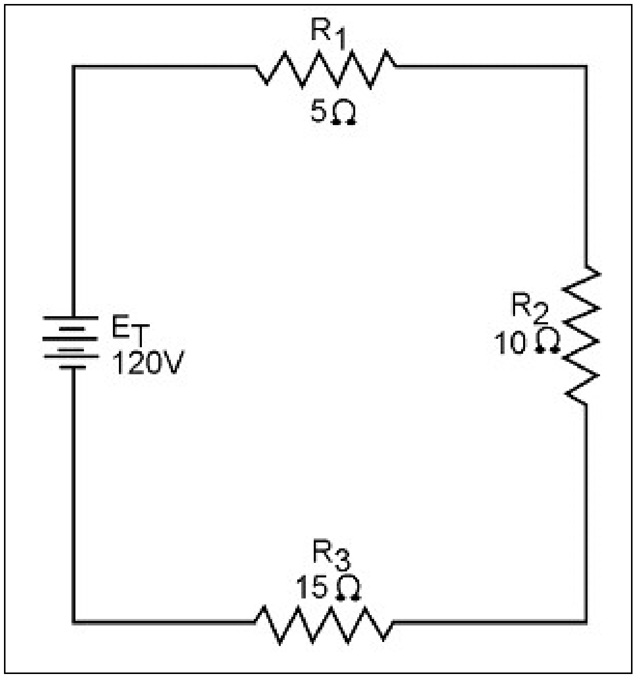

Figure 3-12. Calculating Total Power in a Series Circuit

Equation:

$$P_T = P_1 + P_2 + P_3$$

Given:

R_1 =	5 ohms
R_2 =	10 ohms
R_3 =	15 ohms
E_T =	120 volts

Solution:
First, find the total resistance (R_T)—

R_T =	$R_1 + R_2 + R_3$
R_T =	5 ohms + 10 ohms + 15 ohms
R_T =	30 ohms

Next, calculate the circuit current by using the total resistance and the applied voltage—

$$I = \frac{E_T}{R_T}$$

$$I = \frac{120 \text{ volts}}{30 \text{ ohms}}$$

$$I = 4 \text{ amps}$$

Next, calculate the power for each resistor using the power formulas—

For R_1—

P_1 = $I^2 \times R_1$

P_1 = $(4 \text{ amps})^2 \times 5$ ohms

P_1 = 80 watts

For R2—

P_2 = $I^2 \times R_2$

P_2 = $(4 \text{ amps})^2 \times 10$ ohms

P_2 = 160 watts

For R3—

P_3 = $I^2 \times R_3$

P_3 = $(4 \text{ amps})^2 \times 15$ ohms

P_3 = 240 watts

Then, calculate the total power—

P_T = $P_1 + P_2 + P_3$

P_T = 80 watts + 160 watts + 240 watts

P_T = 480 watts

3-45. To check the answer in the above example, calculate the total power delivered by the source as follows:

P_{source} = $I_{source} \times E_{source}$

P_{source} = 4 amps x 120 volts

P_{source} = 480 watts

RULES FOR SERIES DIRECT CURRENT CIRCUITS

3-46. The important factors governing the operation of a series circuit are listed below. It is important to understand these concepts before studying more advanced circuit theory.

1. The same current flows through each part of a series circuit.

$$I_T = I_1 = I_2 = I_3 = In$$

2. The total resistance of a series circuit equals the sum of the individual resistances.

$$R_T = R_1 + R_2 + R_3 + \ldots R_n$$

3. The total voltage across a series circuit equals the sum of the individual voltage drops.

$$E_T = E_1 + E_2 + E_3 + \ldots E_n$$

4. The voltage drop across a resistor in a series circuit is proportional to the ohmic value of the resistor.

5. The total power in a series circuit equals the sum of the individual powers used by each circuit component.

$$P_T = P_1 + P_2 + P_3 + \ldots P_n$$

SERIES CIRCUIT PROBLEMS

3-47. The following sample problems show the procedure for solving series circuits:

Example: Three resistors of 5 ohms, 10 ohms, and 15 ohms are connected in series with a power source of 90 volts (see Figure 3-13).

a. What is the total resistance?
b. What is the circuit current?
c. What is the voltage drop across each resistor?
d. What is the power of each resistor?
e. What is the total power of the circuit?

In solving the circuit, find the total resistance first (Solution [a]). Next, calculate the circuit current (Solution [b]). Once the current is known, calculate the voltage drops (Solution [c]) and power dissipations (Solution [d]).

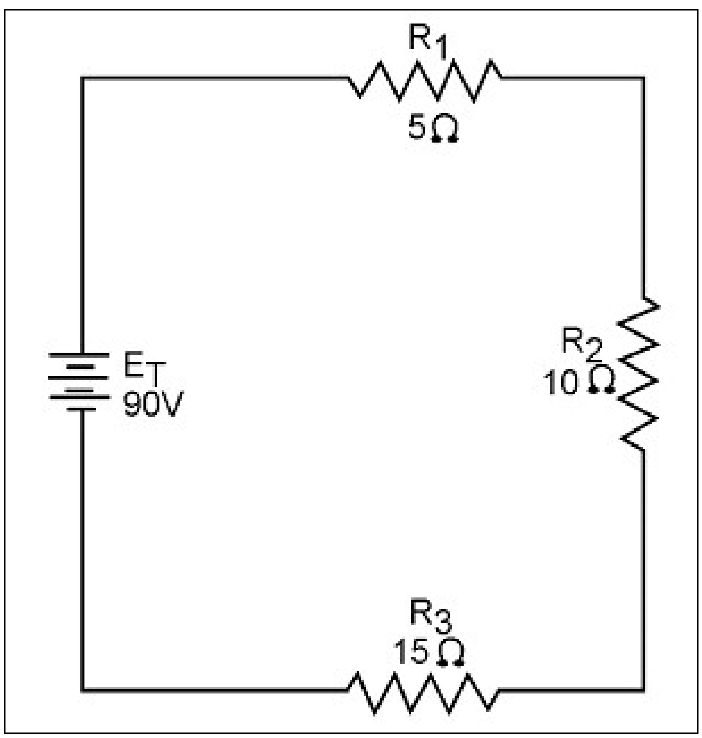

Figure 3-13. Solving for Various Values in a Series Circuit

Given:

R_1 = 5 ohms

R_2 = 10 ohms

R_3 = 15 ohms

E_T = 90 volts

Solution (a):

$R_T = R_1 + R_2 + R_3$

R_T = 5 ohms + 10 ohms + 15 ohms

R_T = 30 ohms

Solution (b):

$I = \frac{E_T}{R_T}$

$I = \frac{90 \text{ volts}}{30 \text{ ohms}}$

I = 3 amps

Solution (c):

$E_1 = I \times R_1$

E_1 = 3 amps x 5 ohms

E_1 = 15 volts

$E_2 = I \times R_2$

E_2 = 3 amps x 10 ohms

E_2 = 30 volts

$E_3 = I \times R_3$

E_3 = 3 amps x 15 ohms

E_3 = 45 volts

Solution (d):

$P_1 = I \times E_1$

P_1 = 3 amps x 15 volts

P_1 = 45 watts

$P_2 = I \times E_2$

P_2 = 3 amps x 30 volts

P_2 = 90 watts

$P_3 = I \times E_3$

P_3 = 3 amps x 45 volts

P_3 = 135 watts

Solution (e):

P_T = E_T x I

P_T = 90 volts x 3 amps

P_T = 270 watts

Or:

P_T = $P_1 + P_2 + P_3$

P_T = 45 watts + 90 watts + 135 watts

P_T = 270 watts

Example: Four resistors (R_1 = 10 ohms, R_2 = 10 ohms, R_3 = 50 ohms, and R_4 = 30 ohms) are connected in series with a power source (see Figure 3-14). The current through the circuit is 1/2 ampere.

a. What is the battery voltage?
b. What is the voltage across each resistor?
c. What is the power expended in each resistor?
d. What is the total power?

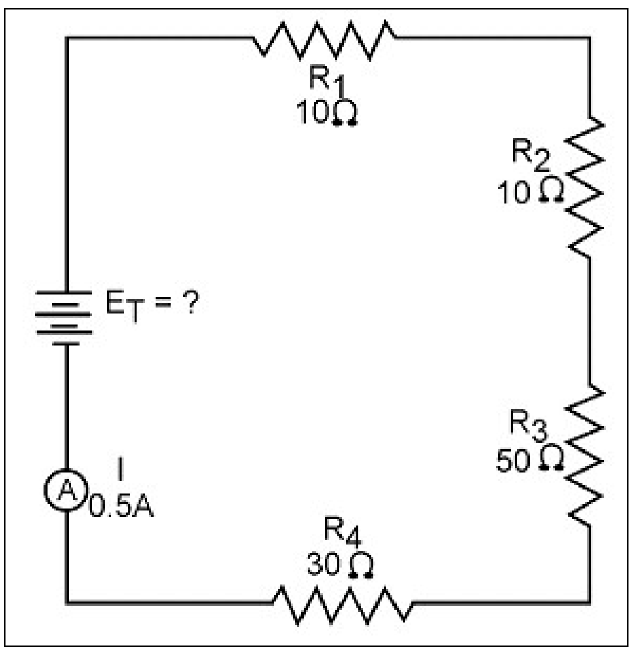

Figure 3-14. Computing Series Circuit Values

Given:

R_1 = 10 ohms

R_2 = 10 ohms

R_3 = 50 ohms

R_4 = 30 ohms

I = 0.5 amp

Solution (a):

E_T = $I \times R_T$

R_T = $R_1 + R_2 + R_3 + R_4$

R_T = 10 ohms + 10 ohms + 50 ohms + 30 ohms

R_T = 100 ohms

E_T = 0.5 amp x 100 ohms

E_T = 50 volts

Solution (b):

E_1 = $I \times R_1$

E_1 = 0.5 amp x 10 ohms

E_1 = 5 volts

E_2 = $I \times R_2$

E_2 = 0.5 amp x 10 ohms

E_2 = 5 volts

E_3 = $I \times R_3$

E_3 = 0.5 amp x 50 ohms

E_3 = 25 volts

E_4 = $I \times R_4$

E_4 = 0.5 amp x 30 ohms

E_4 = 15 volts

Solution (c):

P_1 = $I \times E_1$

P_1 = 0.5 amp x 5 volts

P_1 = 2.5 watts

P_2 = $I \times E_2$

P_2 = 0.5 amp x 5 volts

P_2 = 2.5 watts

P_3 = $I \times E_3$

P_3 = 0.5 amp x 25 volts

P_3 = 12.5 watts

P_4 = $I \times E_4$

P_4 = 0.5 amp x 15 volts

P_4 = 7.5 watts

Solution (d):

P_T = $P_1 + P_2 + P_3 + P_4$

P_T = 2.5 watts + 2.5 watts + 12.5 watts + 7.5 watts

P_T = 25 watts

Or:

$$P_T = \frac{E_T^2}{R_T}$$

$$P_T = \frac{(50 \text{ volts})^2}{100 \text{ ohms}}$$

$$P_T = \frac{2{,}500 \text{ volts}}{100 \text{ volts}}$$

$$P = 25 \text{ watts}$$

3-48. When applying Ohm's law to a series circuit, consider whether the values used are component values or total values. When the information available enables the use of Ohm's law to find total resistance, total voltage, total current, and total values must be inserted into the formula.

To find total resistance—

$$R_T = \frac{E_T}{I_T}$$

To find total voltage—

$$E_T = I_T \text{ x } R_T$$

To find total current—

$$I_T = \frac{E_T}{R_T}$$

Note: In a series circuit, I_T = I. However, the distinction between I_T and I in the formula should be noted because future circuits may have several currents. Therefore, it would be necessary to differentiate between I_T and other currents.

3-49. To compute any quantity (E, I, R, or P) associated with a single given resistor, obtain the values used in the formula from that particular resistor. For example, to find the value of an unknown resistance, use the voltage across and the current through that particular resistor.

To find the value of a resistor—

$$R_x = \frac{E_x}{I_x}$$

To find the voltage drop across a resistor—

$$E_x = (I_x)\,(R_x)$$

To find current through a resistor—

$$I_x = \frac{E_x}{R_x}$$

KIRCHHOFF'S VOLTAGE LAW

3-50. In 1847, G. R. Kirchhoff extended the use of Ohm's law by developing a simple concept concerning the voltages contained in a series circuit loop. Kirchhoff's law states that the algebraic sum of the voltage drops in any closed path in a circuit and the electromotive forces in that path is equal to zero.

3-51. To state Kirchhoff's law another way, the total voltage drops and voltage sources in a circuit are equal at any given moment in time. If the voltage sources are assumed to have one sign (positive or negative) $E_T = I_T \times R_T$ at that instant and the voltage drops are assumed to have the opposite sign, the result of adding the voltage sources and voltage drops will be zero.

Note: The terms "electromotive force" and "EMF" are used when explaining Kirchhoff's law because Kirchhoff's law is used in AC circuits (covered in later chapters). In applying Kirchhoff's law to DC circuits, the terms "electromotive force" and "EMF" apply to voltage sources such as batteries or power supplies.

3-52. Using Kirchhoff's law, circuit problems can be solved that would be difficult, and often impossible, with only the knowledge of Ohm's law. When Kirchhoff's law is properly applied, an equation can be set up for a closed loop and the unknown circuit values can be calculated.

Example: Three resistors are connected across a 50-volt source. What is the voltage across the third resistor if the voltage drops across the first two resistors are 25 volts and 15 volts?

Equation:
The basic series voltage rule states—

$$\mathbf{E_T = E_1 + E_2 + E_3}$$

Given:

E_1 = 25 volts

E_2 = 15 volts

E_T = 50 volts

Solution:
Since the voltages of E_1 and E_2 as well as the voltage supply E_T are given, the equation can be rewritten with the known values—

50 volts = 25 volts + 15 volts + E_x (the unknown factor)

Therefore—

E_x = 50 volts – 25 volts – 15 volts

E_x = 10 volts

3-53. Using this same idea, many electrical problems can be solved, not by knowing all the mysterious properties of electricity, but by understanding the basic principles of mathematics. This algebraic expression can be used for all equations, not just for voltage, current, and resistance.

CIRCUIT TERMS AND CHARACTERISTICS

3-54. You should become familiar with some of the terms and characteristics used in electrical circuits before you learn about the types of circuits. The following terms and characteristics used in electrical circuits are used throughout the study of electricity and electronics.

Open Circuit

3-55. A circuit is open when a break interrupts a complete conducting pathway. Although an open circuit normally occurs when a switch is used to de-energize a circuit, one may also develop accidentally. To restore a circuit to proper operation, the opening must be located, its cause determined, and repairs made.

3-56. Sometimes an open circuit can be located visually by close inspection of the circuit components. Defective components (such as burned out resistors) can usually be discovered by this method. Others (such as a break in wire covered by insulation or the melted element of an enclosed fuse) are not visible to the eye. Under such conditions, understanding the effect an open circuit has on circuit conditions enables a technician to use test equipment to locate the open component.

3-57. In Figure 3-15, the series circuit consists of two resistors and a fuse. Notice the effects on circuit conditions when the fuse opens. Current ceases to flow. Therefore, there is no longer a voltage drop across the resistors. Each end of the open circuit-conducting path becomes an extension of the battery terminals and the voltage felt across the open circuit equals the applied voltage (E_T).

3-58. An open circuit has infinite resistance. Infinity represents a quantity so large it cannot be measured. The symbol for infinity is ~. In an open circuit, R_T = ~.

Short Circuit

3-59. A short circuit is an accidental path of low resistance that passes an abnormally high amount of current. A short circuit exists whenever the resistance of a circuit or the resistance of a part of a circuit drops in value to almost 0 ohms. A short often occurs as a result of improper wiring or broken insulation.

3-60. Figure 3-16 shows a short caused by improper wiring. Note the effect on current flow. Since the resistor (R_1) has in effect been replaced with a piece of wire, practically all the current flows through the short and very little current flows through the resistor (R_1). Electrons flow through the short (a path of almost zero resistance) and the remainder of the circuit by passing through the 10-ohm resistor (R_2) and the battery. The amount of current flow increases greatly because its resistive path has decreased from 10,000 ohms to 10 ohms. Due to the excessive current flow, the 10-ohm resistor (R_2) becomes heated. The resistor will probably be destroyed as it tries to dissipate this heat. Figure 3-17 shows a pictorial wiring diagram, rather than a schematic diagram, to indicate how broken insulation might cause a short circuit.

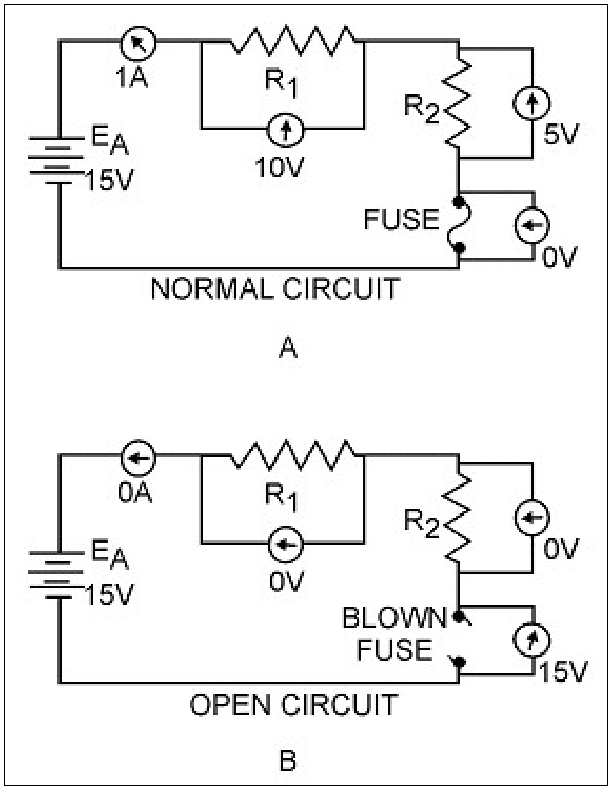

Figure 3-15. Normal and Open Circuit

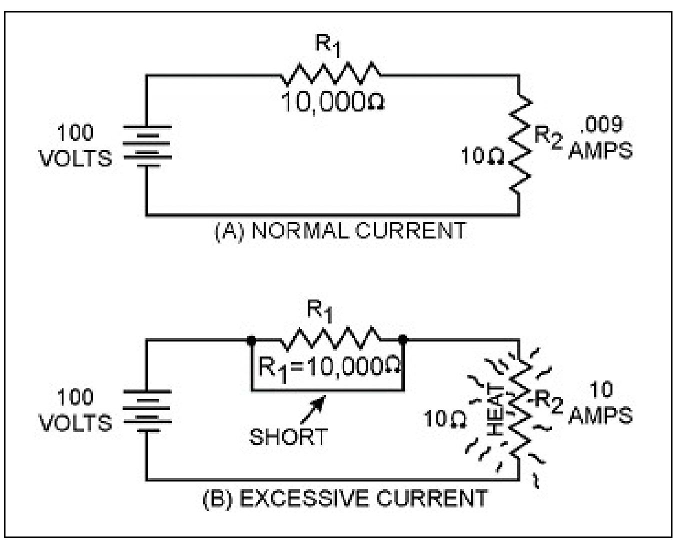

Figure 3-16. Normal and Short Circuit Conditions

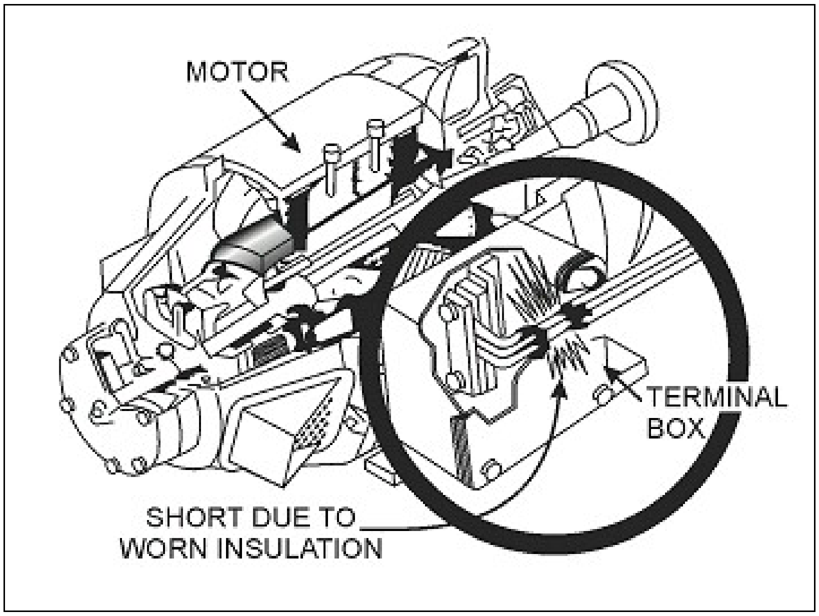

Figure 3-17. Short Due to Broken Insulation

Source Resistance

3-61. A meter connected across the terminals of a good 1.5-volt battery reads about 1.5 volts. When the same battery is inserted into a complete circuit, the meter reading decreases to less than 1.5 volts. The internal resistance of the battery (the opposition to current offered by the electrolyte in the battery) causes this difference in terminal voltage. All sources of EMF have some form of internal resistance that causes a drop in terminal voltage as current flows through the source.

3-62. Figure 3-18 illustrates this principle by showing the internal resistance of a battery as R_i. In the schematic, an additional resistor in series with the battery indicates the internal resistance. With the switch open (view A), the voltage across the battery terminals reads 15 volts. When the switch is closed (view B) current flow causes voltage drops around the circuit. The circuit current of 2 amperes causes a voltage drop of 2 volts across R_1. The 1-ohm internal battery resistance thereby drops the battery terminal voltage to 13 volts. Internal resistance cannot be measured directly with a meter. An attempt to do this would damage the meter.

Power Transfer and Efficiency

3-63. Maximum power is transferred from the source to the load when the resistance of the load equals the internal resistance of the source. The table and the graph in Figure 3-19 (views A and B) illustrate this theory. When the load resistance is 5 ohms, matching the source resistance, the maximum power of 500 watts is developed in the load.

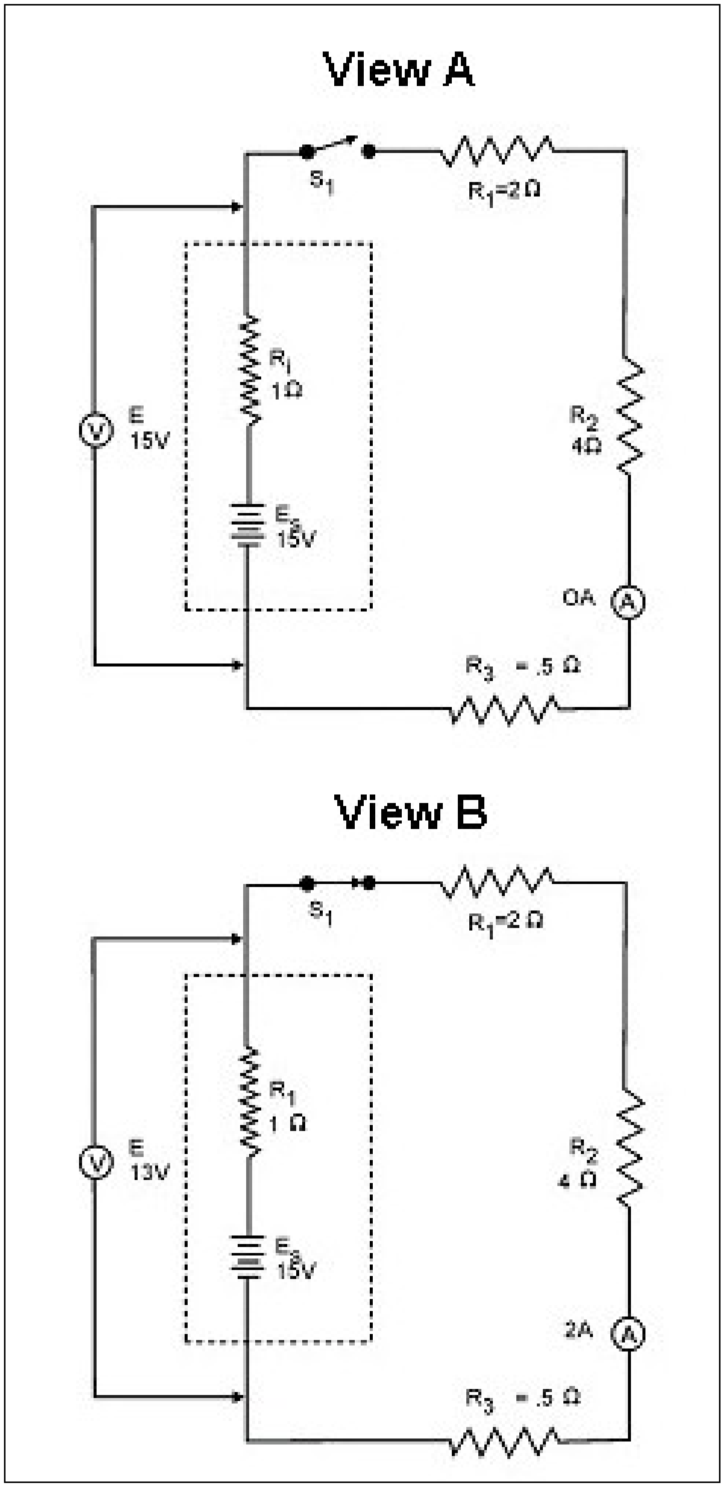

Figure 3-18. Effect of Internal Source

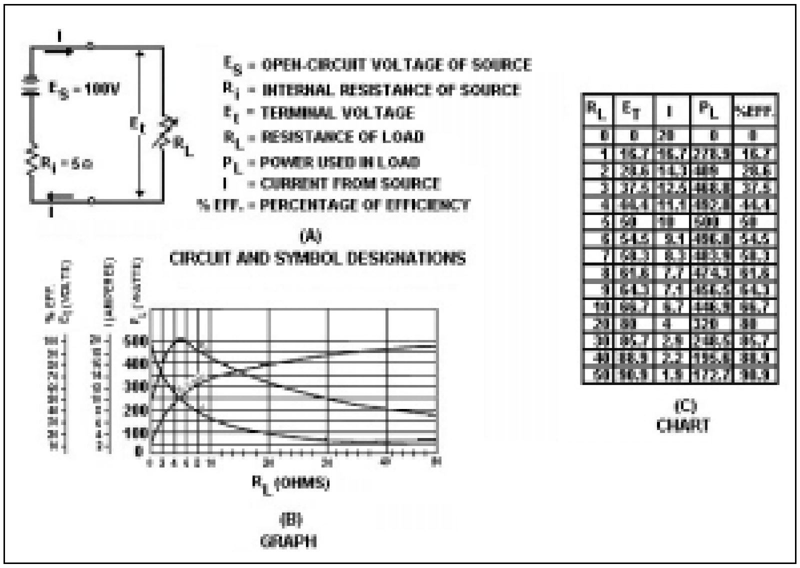

Figure 3-19. Effect of Source Resistance on Power Output

3-64. The efficiency of power transfer (ratio of output power to input power) from the source to the load increases as the load resistance is increased. The efficiency approaches 100 percent as the load's resistance approaches a relatively large value compared with that of the source, because less power is lost in the source. The efficiency of power transfer is only 50 percent at the maximum power transfer point (when the load resistance equals the internal resistance of the source). The efficiency of power transfer approaches zero efficiency when the load resistance is relatively small compared with the internal resistance of the source. This is also shown on the chart in Figure 3-19, view C.

3-65. The problem with the desire for both high efficiency and maximum power transfer is resolved by a compromise between maximum power transfer and high efficiency. When the amount of power involved is large and the efficiency is important, the load resistance is made large relative to the source resistance so that the losses are kept small. In this case, the efficiency is high. When the problem of matching a source to a load is important, as in communications circuits, a strong signal may be more important than a high percentage of efficiency. In such cases, the efficiency of power transfer should be only about 50 percent. However, the power transfer would be the maximum the source is capable of supplying.

PARALLEL DIRECT CURRENT CIRCUITS

3-66. The series circuit has only one path for current. Another basic type of circuit is the parallel circuit. While the series circuit has only one path for current, the parallel circuit has more than one path for current. Ohm's law and Kirchhoff's law apply to all electrical circuits, but the characteristics of a parallel DC circuit are different than those of a series DC circuit.

CHARACTERISTICS

3-67. A parallel circuit has more than one current path connected to a common voltage source. Therefore, parallel circuits must contain two or more resistances that are not connected in series. Figure 3-20 shows an example of a basic parallel circuit.

3-68. Start at the voltage source (E_s) and trace counterclockwise around the circuit in Figure 3-20. Two complete and separate paths can be identified in which current can flow. One path is traced from the source, through resistance R_1, and back to the source. The other path is from the source, through resistance R_2, and back to the source.

3-69. **Voltage in a parallel circuit**. The source voltage in a series circuit divides proportionately across each resistor in the circuit. In a parallel circuit, the same voltage is present in each branch (section of a circuit that has a complete path for current). In Figure 3-20, this voltage equals the applied voltage (E_s). This can be expressed in equation form:

$$E_S = E_{R1} = E_{R2}$$

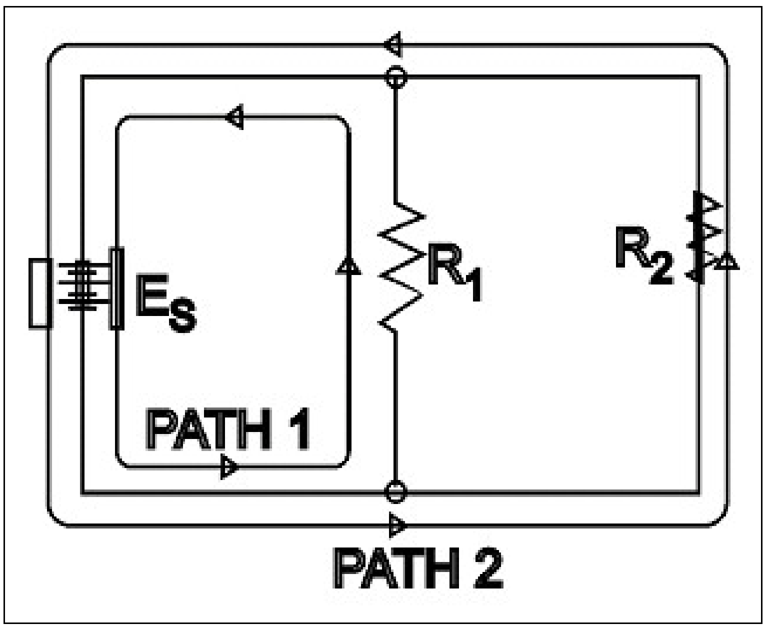

Figure 3-20. Example of a Basic Parallel Circuit

3-70. Voltage measurements taken across the resistors of a parallel circuit verify this equation (see Figure 3-21). Each meter indicates the same amount of voltage. Notice that the voltage across each resistor is the same as the applied voltage.

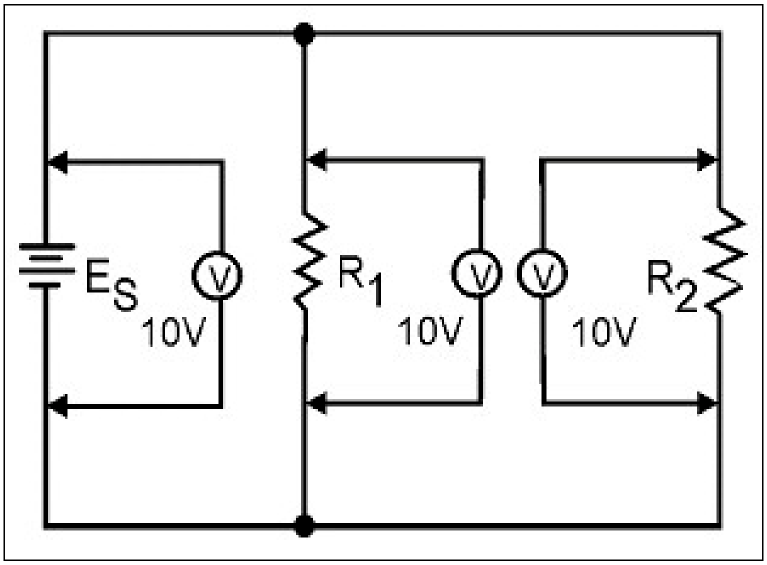

Figure 3-21. Voltage Comparison in a Parallel Circuit

Example: The current through a resistor of a parallel circuit is 12 amperes and the value of the resistor is 10 ohms. Determine the source voltage. Figure 3-22 shows the circuit.

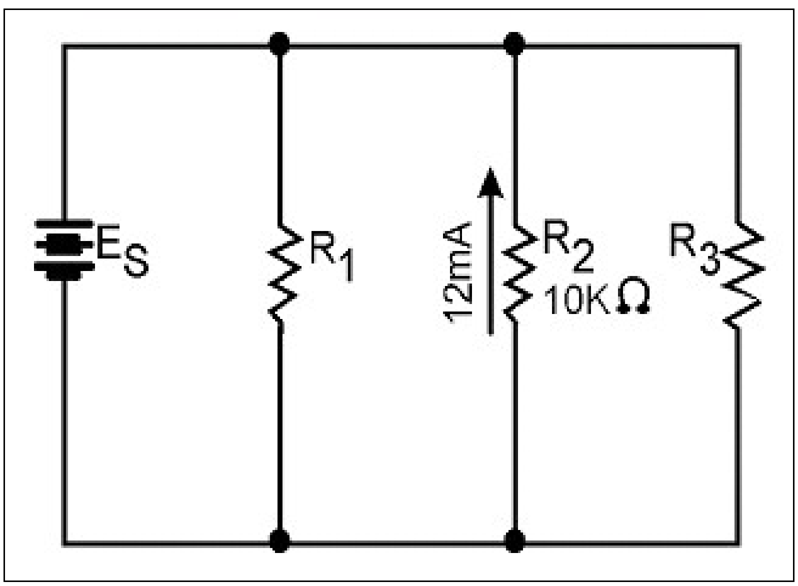

Figure 3-22. Example Problem of a Parallel Circuit

Given:

R_2 = 10 ohms

I_2 = 12 amps

Solution:

First solve for E_2—

$E_2 = I_2 \times R_2$

E_2 = 12 amps x 10 ohms

E_2 = 120 volts

Then, because $E_T = E_2$—

E_T = 120 volts

3-71. **Current in a parallel circuit**. Ohm's law states that the current in a circuit is inversely proportional to the circuit resistance. This is true in both series and parallel circuits.

3-72. There is a single path for current in a series circuit. The amount of current is determined by the total resistance of the circuit and the applied voltage. In a parallel circuit, the source current divides among the available paths.

3-73. The following illustrations show the behavior of current in parallel circuits using sample circuits with different values of resistance for a given value of applied voltage. Figure 3-23, view A, shows a basic series circuit. Here, the total current must pass through the single resistor. The amount of current can be determined as follows:

Given:

E_T = 50 volts

R_1 = 10 ohms

Solution:

$$I = \frac{E}{R}$$

$$I_T = \frac{E_T}{R_1}$$

$$I_T = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_T = 5 \text{ amps}$$

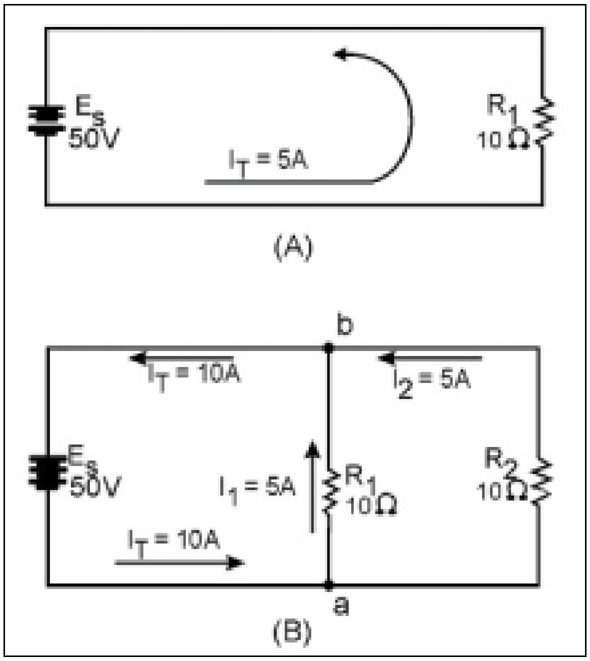

Figure 3-23. Analysis of Current in a Parallel Circuit

Figure 3-23, view B, shows the same resistor (R_1) with a second resistor (R_2) of equal value connected in parallel across the voltage source. When Ohm's law is applied, the current flow through each resistor is found to be the same as the current through the single resistor in Figure 3-23, view A.

Given:

E_T = 50 volts

R_1 = 10 ohms

R_2 = 10 ohms

Solution:

$$I = \frac{E}{R}$$

$$E_T = E_1 = E_2$$

$$I_1 = \frac{E_1}{R_1}$$

$$I_1 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_1 = 5 \text{ amps}$$

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_2 = 5 \text{ amps}$$

3-74. If 5 amperes of current flows through each of the two resistors, there must be a total current of 10 amperes drawn from the source. The total current of 10 amperes leaves the negative terminal of the battery and flows to point “a” (see Figure 3-23, view B). Point “a”, called a node, is a connecting point for the two resistors. At node “a”, the total current divides into two currents of 5 amperes each. These two currents flow through their respective resistors and rejoin at node “b”. The total current then flows from node “b” back to the positive terminal of the source. The source supplies a total current of 10 amperes and each of the two equal resistors carries one-half of the total current.

3-75. Each individual current path in the circuit of view B is a branch. Each branch carries a current that is a portion of the total current. Two or more branches form a network. The characteristics of current in a parallel circuit can be expressed in terms of the following general equation:

$$\mathbf{I_T = I_1 + I_2 \ldots E_n}$$

3-76. Compare Figure 3-24, view A with the circuit in Figure 3-23, view B. Notice that doubling the value of the second branch resistor (R_2) has no effect on the current in the first branch (I_1). However, it does reduce the second branch current (I_2) to one-half its original value. The total circuit current drops to a value equal to the sum of the branch currents. These facts are verified by the following equations:

Given:

E_T = 50 volts

R_1 = 10 ohms

R_2 = 20 ohms

Solution:

$$I = \frac{E}{R}$$

$$E_T = E_1 = E_2$$

$$I_T = \frac{E_1}{R_1}$$

$$I_1 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_1 = 5 \text{ amps}$$

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{50 \text{ volts}}{20 \text{ ohms}}$$

$$I_2 = 2.5 \text{ amps}$$

$$I_T = I_1 + I_2$$

$$I_T = 5 \text{ amps} + 2.5 \text{ amps}$$

$$I_T = 7.5 \text{ amps}$$

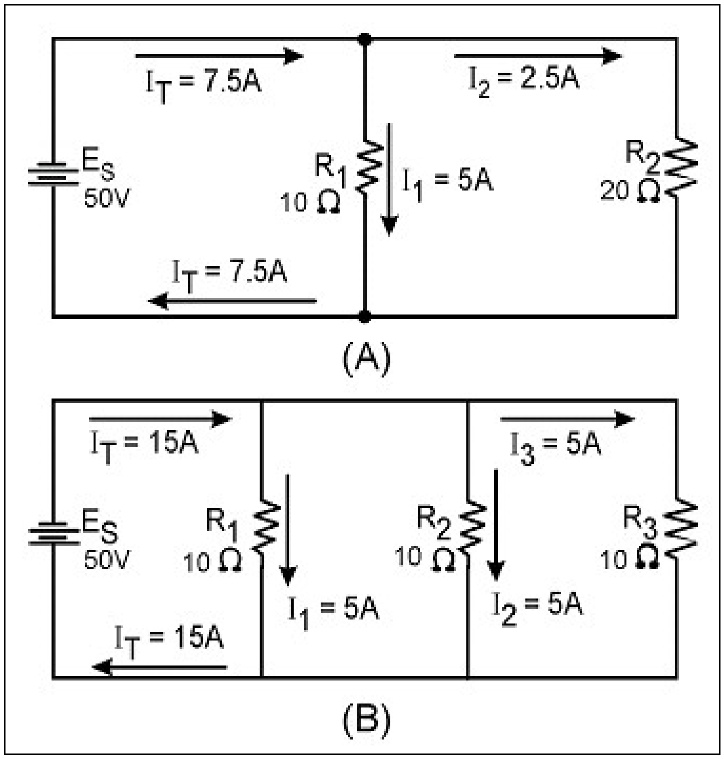

Figure 3-24. Current Behavior in a Parallel Circuit

3-77. The amount of current flow in the branch circuits and the total current in the circuit in Figure 3-24, view B, are determined by the following computations.

Equations:

$$\mathbf{I = \frac{E}{R}}$$

$$\mathbf{E_s = E_1 = E_2 = E_3}$$

Given:

E_T =	50 volts
R_1 =	10 ohms
R_2 =	10 ohms
R_3 =	10 ohms

Solution:

$$I_1 = \frac{E_1}{R_1}$$

$$I_1 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_1 = 5 \text{ amps}$$

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_2 = 5 \text{ amps}$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

$$I_3 = 5 \text{ amps}$$

$$I_T = I_1 + I_2 + I_3$$

$$I_T = 5 \text{ amps} + 5 \text{ amps} + 5 \text{ amps}$$

$$I_T = 15 \text{ amps}$$

Notice that the sum of the ohmic values of the resistors in both circuits in Figure 3-24 is equal (30 ohms) and that the applied voltage is the same value (50 volts). However, the total current in Figure 3-24, view B, (15 amperes) is twice the amount in Figure 3-24, view A, (7.5 amperes). It is apparent, therefore, that the manner in which resistors are connected in a circuit, as well as their actual ohmic values, affect the total current.

3-78. The division of current in a parallel network follows a definite pattern. This pattern is described by Kirchhoff's current law, which states that the algebraic sum of the currents entering and leaving any node of conductors is equal to zero. This law is stated mathematically as—

Ia + Ib + ... In = 0

Where:

Ia, Ib, . . . In = the current entering and leaving the node.

3-79. Currents entering the node are considered positive and currents leaving the node are negative. When solving a problem using Kirchhoff's current law, the currents must be placed into the equation with the proper polarity signs attached.

Example: Solve for the value of I_3 in Figure 3-25.

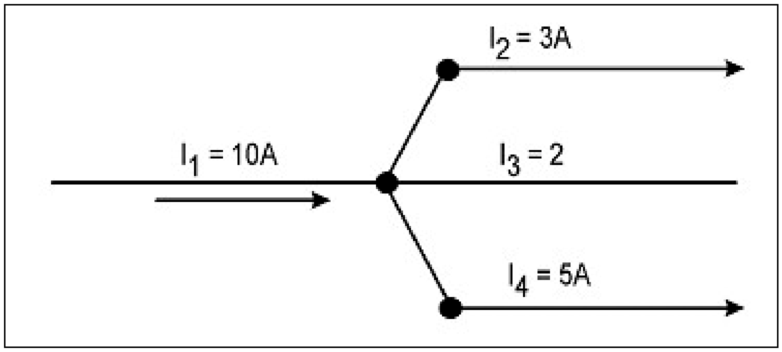

Figure 3-25. Circuit for Example Problem

Equation:

Ia + Ib + ... In = 0

Given:

I_1 = 10 amps

I_2 = 3 amps

I_4 = 5 amps

Solution:

Place the currents into the equation with the proper signs—

$I_1 + I_2 + I_3 + I_4 = 0$

10 amps + (-3 amps) + I_3 + (-5 amps) = 0

I_3 + 2 amps = 0

I_3 = -2 amps

I_3 has a value of 2 amperes. The negative sign shows it to be a current leaving the node.

3-80. **Resistance in a parallel circuit**. The sample diagram (see Figure 3-26) has two resistors connected in parallel across a 5-volt battery. Each has a resistance value of 10 ohms. A complete circuit consisting of two parallel paths is formed and current flows as shown.

3-81. Computing the individual currents shows that there is 1/2 ampere of current through each resistor. The total current flowing from the battery to the node of the resistors and returning from the resistors to the battery equals 1 ampere.

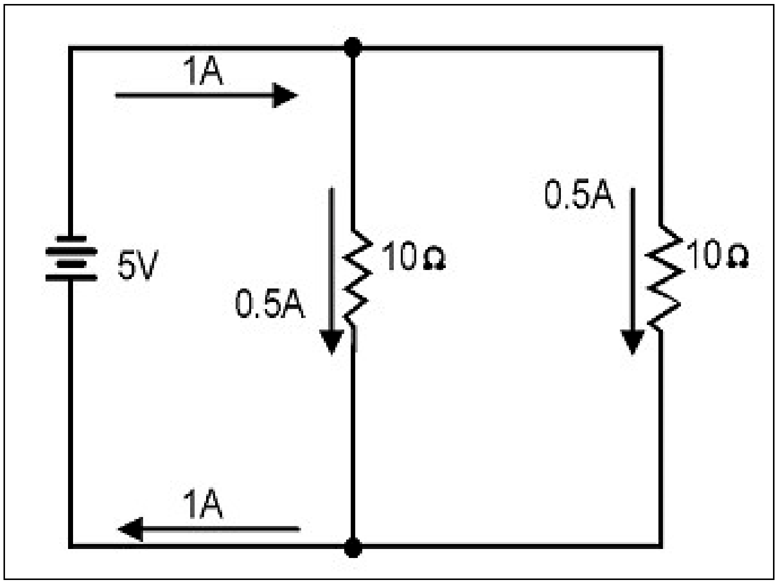

Figure 3-26. Two Equal Resistors Connected

3-82. The total resistance of the circuit is calculated using the values of total voltage (E_T) and total current (I_T):

Equation:

$$R = \frac{E}{I}$$

Given:

E_T = 5 volts

I_T = 1 amp

Solution:

$R = \frac{E}{I}$

$R_T = \frac{E_T}{I_T}$

$R_T = \frac{5 \text{ volts}}{1 \text{ amp}}$

R_T = 5 ohms

This computation shows the total resistance to be 5 ohms, one-half the value of either of the two resistors.

3-83. The total resistance of a parallel circuit is smaller than any of the individual resistors. Therefore, the total resistance of a parallel circuit is not the sum of the individual resistor values as was the case in a series circuit. The total resistance of resistors in parallel is also referred to as equivalent resistance.

3-84. Several methods are used to determine the equivalent resistance of parallel circuits. The best method for a given circuit depends on the number and value of the resistors. For the circuit described above, where all resistors have the same value, the following simple equation is used:

$$\mathbf{R_T = \frac{R}{N}}$$

Where:

R_T =	total parallel resistance
R =	ohmic value of one resistor
N =	number of resistors

This equation is valid for any number of parallel resistors of equal value.

Example: Four 40-ohm resistors are connected in parallel. Use the following equation to determine their equivalent resistance.

Given:

R_1 =	$R_2 = R_3 = R_4$
R_1 =	40 ohms

Solution:

$$R_T = \frac{R}{N}$$

$$R_T = \frac{40 \text{ ohms}}{4}$$

$$R_T = 10 \text{ ohms}$$

3-85. Figure 3-27 shows two resistors of unequal value in parallel. The equivalent resistance can be calculated because the total current is shown.

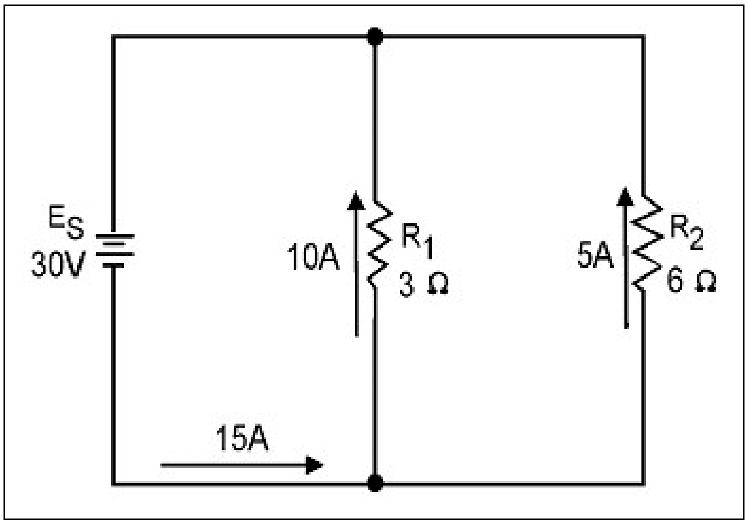

Figure 3-27. Example Circuit With Unequal Parallel Resistors

Given:

$E_T =$ 30 volts

$I_T =$ 15 amps

Solution:

$$R_T = \frac{E_T}{I_T}$$

$$R_T = \frac{30 \text{ volts}}{15 \text{ amps}}$$

$R_T =$ 2 ohms

3-86. The total resistance of the circuit in Figure 3-27 is smaller than either of the two resistors (R_1, R_2). An important point to remember is that the total resistance of a parallel circuit is always less than the resistance of any branch.

3-87. **Reciprocal method**. This method is based on taking the reciprocal of each side of the equation. This presents the general formula for resistors in parallel as shown in the following:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

This formula is generally used to solve for the equivalent resistance of any number of unequal parallel resistors. Unlike the equal value or the product-over-the-sum method, the reciprocal method is the only formula that can be used to determine the equivalent resistance in any combination of parallel resistances. You must find the lowest common denominator in solving these problems.

Example: Three resistors are connected in parallel as shown in Figure 3-28. The resistor values are R_1 = 20 ohms, R_2 = 30 ohms, and R_3 = 40 ohms. Using the reciprocal method, determine the equivalent resistance.

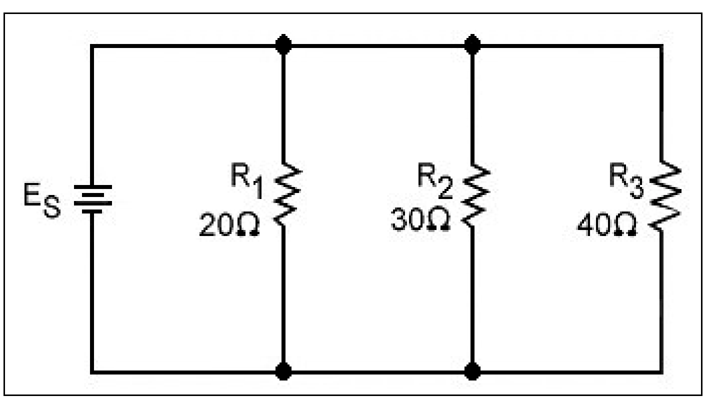

Figure 3-28. Example of a Parallel Circuit With Unequal Branch Resistors

Given:

R_1 = 20 ohms

R_2 = 30 ohms

R_3 = 40 ohms

Solution:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{1}{\frac{1}{20 \text{ ohms}} + \frac{1}{30 \text{ ohms}} + \frac{1}{40 \text{ ohms}}}$$

$$R_T = \frac{1}{\frac{6}{120 \text{ ohms}} + \frac{4}{120 \text{ ohms}} + \frac{3}{120 \text{ ohms}}}$$

$$R_T = \frac{13}{120 \text{ ohms}}$$

$$R_T = \frac{120 \text{ ohms}}{13}$$

$$R_T = 9.23 \text{ ohms}$$

3-88. **Product-over-the-sum method**. A convenient method for finding the equivalent (or total) resistance of two parallel resistors is by using the following product-over-the-sum formula:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Example: What is the equivalent resistance of a 20-ohm and a 30-ohm resistor connected in parallel, as in Figure 3-29?

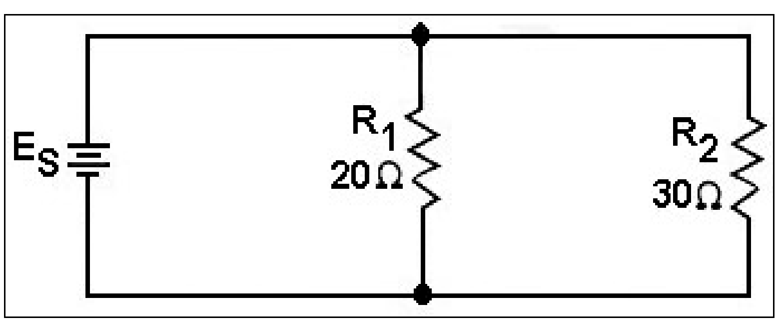

Figure 3-29. Parallel Circuit With Two Unequal Resistors

Given:

R_1 = 20

R_2 = 30

Solution:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{20 \text{ ohms} \times 30 \text{ ohms}}{20 \text{ ohms} + 30 \text{ ohms}}$$

$$R_T = \frac{600 \text{ ohms}}{50 \text{ ohms}}$$

$$R_T = 12 \text{ ohms}$$

The product-over-the-sum method can be used only with two resistance values at a time. If three or more resistors are to be calculated, combine any two ohmic values into an equivalent resistance using the formula. Repeat the formula again, and this time, combine the remaining ohmic value with the recently derived equivalent resistance. Combining additional resistance values with equivalent resistance may be continued throughout the parallel circuit.

3-89. **Power in a parallel circuit**. Power computations in a parallel circuit are basically the same as those used for the series circuit. Since power dissipation in resistors consists of a heat loss, power dissipations are additive, regardless of how the resistors are connected in the circuit. The total power equals the sum of the power dissipated by the individual resistors. Like the series circuit, the total power consumed by the parallel circuit is determined using the following equation:

$$P_T = P_1 + P_2 + \ldots P_n$$

Example: Find the total power consumed by the circuit in Figure 3-30.

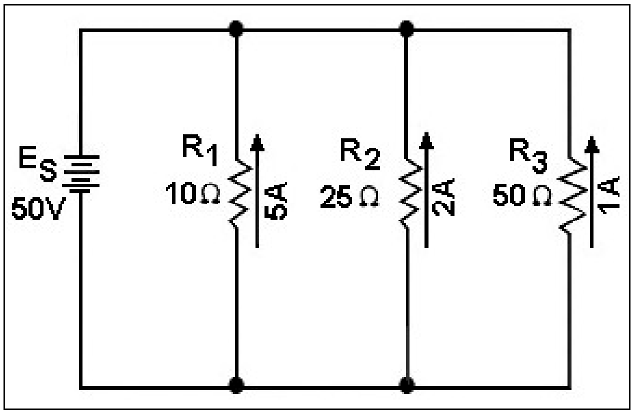

Figure 3-30. Example of a Parallel Circuit

Given:

R_1 = 10 ohms

I_1 = 5 amps

R_2 = 25 ohms

I_2 = 2 amps

R_3 = 50 ohms

I_3 = 1 amp

Solution:

$P = I^2R$

$P_1 = (I_1)^2 \times R_1$

$P_1 = (5 \text{ amps})^2 \times 10 \text{ ohms}$

$P_1 = 250 \text{ watts}$

$P_2 = (I_2)^2 \times R_2$

$P_2 = (2 \text{ amps})^2 \times 25 \text{ ohms}$

$P_2 = 100 \text{ watts}$

$P_3 = (I_3)^2 \times R_3$

$P_3 = (1 \text{ amp})^2 \times 50 \text{ ohms}$

$P_3 = 50 \text{ watts}$

$P_T = P_1 + P_2 + P_3$

$P_T = 250 \text{ watts} + 100 \text{ watts} + 50 \text{ watts}$

$P_T = 400 \text{ watts}$

Since the total current and source voltage are known, one can also compute the total power as follows:

Given:

E_T = 50 volts

I_T = 8 amps

Solution:

$P_T = E_T \times I_T$

$P_T = 50 \text{ volts} \times 8 \text{ amps}$

$P_T = 400 \text{ watts}$

EQUIVALENT CIRCUITS

3-90. Sometimes, it is often necessary to reduce a complex circuit into a simpler form. Any complex circuit consisting of resistances can be redrawn (reduced) to a basic equivalent circuit containing the voltage source and a single resistor representing total resistance. This process is called reduction to an equivalent circuit.

3-91. Figure 3-31 shows a parallel circuit with three resistors of equal value and the redrawn equivalent circuit. The parallel circuit in view A shows the original circuit. To create the equivalent circuit, first calculate the equivalent resistance:

Given:

R_1 = 45 ohms

R_2 = 45 ohms

R_3 = 45 ohms

Solution:

$$R_T = \frac{R}{N}$$

$$R_T = \frac{45 \text{ ohms}}{3}$$

$$R_T = 15 \text{ ohms}$$

Once the equivalent resistance is known, a new circuit is drawn consisting of a single resistor (to represent the equivalent resistance) and the voltage source (see Figure 3-31, view B).

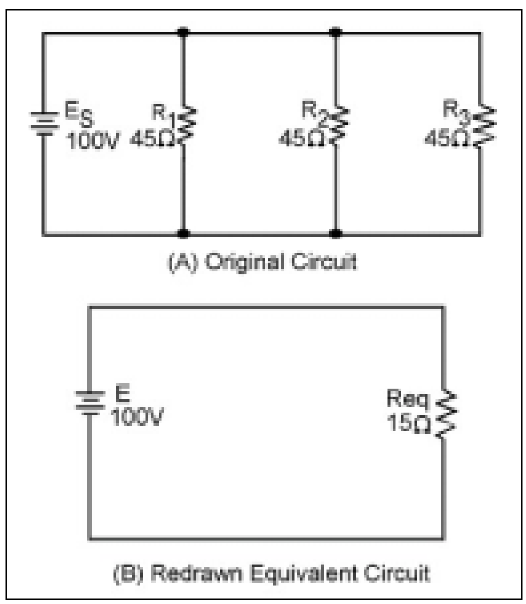

Figure 3-31. Parallel Circuit With Equivalent Circuit

3-92. The reduction of the electrical circuit from a complex parallel circuit to the simple single resistor series circuit may appear to distort the original circuit drastically and apply only to the mathematical electrical rules. However, this is the basic electrical schematic that a power source sees. The generator or battery only sees one single series electrical load. The load determines the total resistance (R_T) that the generator must deal with. Based on this, the generator supplies the current (I_T), pushed through the circuits by the voltage (E_T). The electrical wiring system of series and parallel combinations and various electrical loads will require the current to be divided up effectively, as seen with Kirchhoff's current law.

RULES FOR PARALLEL DIRECT CURRENT CIRCUITS

3-93. The following are rules for parallel DC circuits:

1. The same voltage exists across each branch of a parallel circuit and equals the source voltage.

$$E_T = E_1 = E_2 = E_3 = E_n$$

2. The total current of a parallel circuit equals the sum of the individual branch currents of the circuit.

$$I_T = I_1 + I_2 + I_3 + In$$

3. The total resistance of a parallel circuit is found by the general formula **($1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_n$)** or one of the formulas derived from this general formula.

4. The total power consumed in a parallel circuit equals the sum of the power consumptions of the individual resistance.

$$P_T = P_1 + P_2 + P_3 + P_n$$

PARALLEL CIRCUIT PROBLEMS

3-94. Problems involving the determination of resistance, voltage, current, and power in a parallel circuit are solved as simply as in a series circuit. The procedure is the same:

1. Draw the circuit diagram.

2. State the values given and the values to be found.

3. Select the equations to be used in solving for the unknown quantities based on the known quantities.

4. Substitute the known values in the selected equation and solve for the unknown value.

Consider the example below:

Example: A parallel circuit consists of five resistors. The value of each resistor is known and the current through R_1 is known. Calculate the value for total resistance, total power, total current, source voltage, the power used by each resistor, and the current through resistors R_2 R_3, R_4, and R_5. In other words, find R_T, E_T, I_T, P_T, I_2, I_3, I_4, I_5, P_1, P_2, P_3, P_4, and P_5.

Given:

R_1 =	20 ohms
R_2 =	30 ohms
R_3 =	18 ohms
R_4 =	18 ohms
R_5 =	18 ohms
I_1 =	9 amps

This may seem to be a large amount of mathematical manipulation. However, the step-by-step approach simplifies the calculation. The first step in solving this problem is to draw the circuit and indicate the known values (see Figure 3-32).

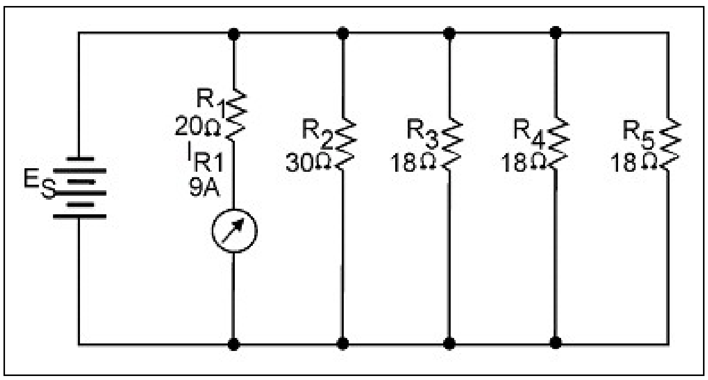

Figure 3-32. Parallel Circuit Problem

3-95. There are several ways to approach this problem. With the given values, you could first solve for R_T, the power used by R_1, or the voltage across R_1, which is equal to the source voltage and the voltage across each of the other resistors. Solving for R_T or the power used by R_1 will not help in solving for the other unknown values.

3-96. Once the voltage across R_1 is known, this value will help in calculating other unknowns. Therefore, the logical unknown to solve for first is the source voltage (the voltage across R_1).

Given:

R_1 =	20 ohms
I_1 =	9 amps
E_1 =	E_T

Solution:

E_T = $R_1 \times I_1$

E_T = 9 amps x 20 ohms

E_T = 180 volts

Now that source voltage is known, you can solve for current in each branch—

Given:

E_T = 180 volts

R_2 = 30 ohms

R_3 = 18 ohms

R_4 = 18 ohms

R_5 = 18 ohms

Solution:

$$I_2 = \frac{E_T}{R_2}$$

$$I_2 = \frac{180 \text{ volts}}{30 \text{ ohms}}$$

I_2 = 6 amps

$$I_3 = \frac{E_T}{R_3}$$

$$I_3 = \frac{180 \text{ volts}}{18 \text{ ohms}}$$

I_3 = 10 amps

Since $R_3 = R_4 = R_5$ and the voltage across each branch is the same—

I_4 = 10 amps

I_5 = 10 amps

Now solve for total resistance—

Given:

R_1 = 20 ohms

R_2 = 30 ohms

R_3 = 18 ohms

R_4 = 18 ohms

R_5 = 18 ohms

Solution:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5}$$

$$\frac{1}{R_T} = \frac{1}{20} + \frac{1}{30} + \frac{1}{18} + \frac{1}{18} + \frac{1}{18}$$

$$\frac{1}{R_T} = \frac{9 + 6 + 10 + 10 + 10}{180}$$

$$\frac{1}{R_T} = \frac{45}{180}$$

$$R_T = \frac{180}{45}$$

$$R_T = 4 \text{ ohms}$$

3-97. An alternate method for solving R_T can be used. By observation, you can see that R_3, R_4, and R_5 have equal ohmic values. Therefore, an equivalent resistor can be substituted for these three resistors in solving for total resistance—

Given:

$R_3 = R_4 = R_5 = 18$ ohms

Solution:

$$R_1 = \frac{R}{N}$$

$$R_1 = \frac{18 \text{ ohms}}{3}$$

$$R_1 = 6 \text{ ohms}$$

The circuit is now redrawn again using a resistor labeled Req 1 in place of R_3, R_4, and R_5 (see Figure 3-33).

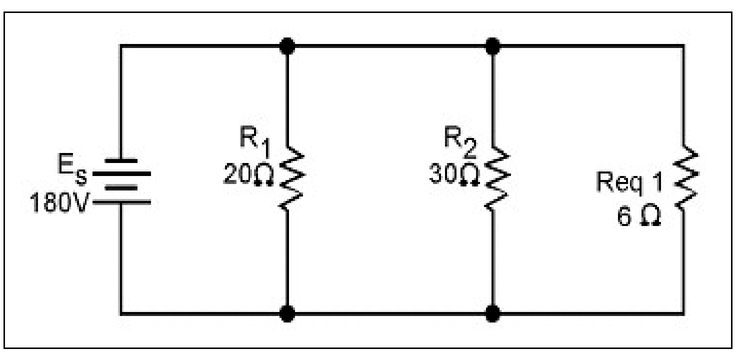

Figure 3-33. First Equivalent Parallel Circuit

An equivalent resistor can be calculated and substituted for R_1 and R_2 by use of the product-over-the-sum formula—

Given:

R_1 =	20 ohms
R_2 =	30 ohms

Solution:

$$R_2 = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_2 = \frac{20 \times 30}{20 + 30}$$

$$R_2 = \frac{600}{50}$$

$$R_2 = 12 \text{ ohms}$$

The circuit is now redrawn using a resistor labeled Req 2 in place of R_1 and R_2 (see Figure 3-34).

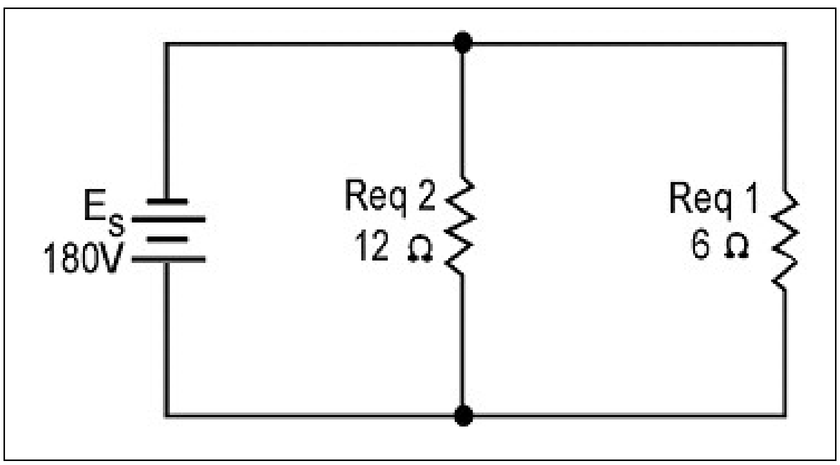

Figure 3-34. Second Equivalent Parallel Circuit

Two resistors are now left in parallel. The product-over-the-sum method can now be used to solve for total resistance—

Given:

R_1 =	6 ohms
R_2 =	12 ohms

Solution:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{6 \text{ ohms} \times 12 \text{ ohms}}{6 \text{ ohms} + 12 \text{ ohms}}$$

$$R_T = \frac{72 \text{ ohms}}{18 \text{ ohms}}$$

$$R_T = 4 \text{ ohms}$$

This result agrees with the solution found by using the general formula for solving for resistors in parallel. The circuit can now be redrawn as shown in Figure 3-35 and the total current can be calculated.

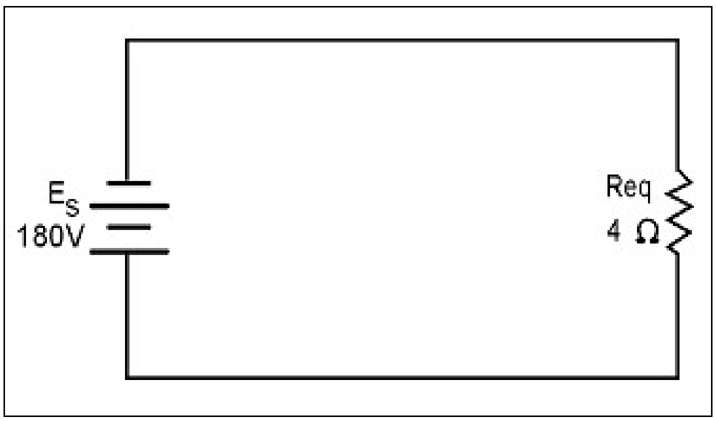

Figure 3-35. Parallel Circuit Redrawn to Final Equivalent Circuit

Given:

E_T = 180 volts

R_T = 4 ohms

Solution:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{180 \text{ volts}}{4 \text{ ohms}}$$

$$I_T = 45 \text{ amps}$$

Check this solution by using the values already calculated for the branch currents—

Given:

I_1 =	9 amps
I_2 =	6 amps
I_3 =	10 amps
I_4 =	10 amps
I_5 =	10 amps

Solution:

I_T =	$I_1 + I_2 + ... In$
I_T =	9 amps + 6 amps + 10 amps + 10 amps + 10 amps
I_T =	45 amps

Now that total current is known, the next logical step is to find total power—

Given:

E_T =	180 volts
I_T =	45 amps

Solution:

P =	E x I
P_T =	E_T x I_T
P_T =	180 volts x 45 amps
P_T =	8,100 watts = 8.1 kW

Solve for the power in each branch—

Given:

E_T =	180 volts
I_1 =	9 amps
I_2 =	6 amps
I_3 =	10 amps
I_4 =	10 amps
I_5 =	10 amps

Solution:

P =	EI
P_1 =	$E_T \times I_1$
P_1 =	189 volts x 9 amps
P_1 =	1,620 watts
P_2 =	$E_T \times I_2$
P_2 =	180 volts x 6 amps
P_2 =	1,080 watts
P_3 =	$E_T \times I_3$
P_3 =	180 volts x 10 amps
P_3 =	1,800 watts

Since $\mathbf{I_3 = I_4 = I_5}$, then $\mathbf{P_3 = P_4 = P_5 = 1{,}800}$ **watts**. The previous calculation for total power can now be checked—

Given:

P_1 =	1,620 watts
P_2 =	1,080 watts
P_3 =	1,800 watts
P_4 =	1,800 watts
P_5 =	1,800 watts

Solution:

P_T =	$P_1 + P_2 + P_3 + P_4 + P_5$
P_T =	1,620 watts + 1,080 watts + 1,800 watts + 1,800 watts + 1,800 watts
P_T =	8,100 watts
P_T =	8.1 kW

SERIES-PARALLEL DIRECT CURRENT CIRCUITS

3-98. Engineers encounter circuits consisting of both series and parallel elements. This type of circuit is called a series-parallel network. Solving for the quantities and elements in a series-parallel network is simply a matter of applying the laws and rules already discussed.

COMBINATION-CIRCUIT PROBLEMS

3-99. The basic technique used for solving DC combination-circuit problems is the use of equivalent circuits. To simplify a complex circuit to a simple circuit containing only one load, equivalent circuits are substituted (on paper) for the complex circuit they represent.

3-100. To demonstrate the method used to solve series-parallel networks problems, the network in Figure 3-36, view A will be used to calculate various circuit quantities (such as resistance, current, voltage, and power).

3-101. Examination of the circuit shows that the only quantity that can be computed with the given information is the equivalent resistance of R_2 and R_3.

Given:

R_2 = 20 ohms

R_3 = 30 ohms

Solution:

$$R_{2,3} = \frac{R_2 \times R_3}{R_2 + R_3} \quad \text{(product over the sum)}$$

$$R_{2,3} = \frac{20 \times 30}{20 + 30}$$

$$R_{2,3} = \frac{600}{50}$$

$$R_{2,3} = 12 \text{ ohms}$$

Now that the equivalent resistance for R_2 and R_3 has been calculated, the circuit can be redrawn as a series circuit (see Figure 3-36, view B). The equivalent resistance of this circuit (total resistance) can now be calculated—

Given:

R_1 = 8 ohms (resistors in series)

$R_{2,3}$ = 12 ohms

Solution:

$R_T = R_1 + R_{2,3}$

$R_T = 8 + 12$

R_T = 20 ohms

3-102. The original circuit can be redrawn with a single resistor that represents the equivalent resistance of the entire circuit (see Figure 3-36, view C). To find total current in the circuit—

Given:

E_T = 60 volts

R_T = 20 ohms

Solution:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{60 \text{ volts}}{20 \text{ ohms}} \quad \text{(Ohm's law)}$$

$$I_T = 3 \text{ amps}$$

3-103. To find total power in the circuit—

Given:

E_T = 60 volts

I_T = 3 amps

Solution:

$P_T = E_T \times I_T$

P_T = 60 volts x 3 amps

P_T = 180 watts

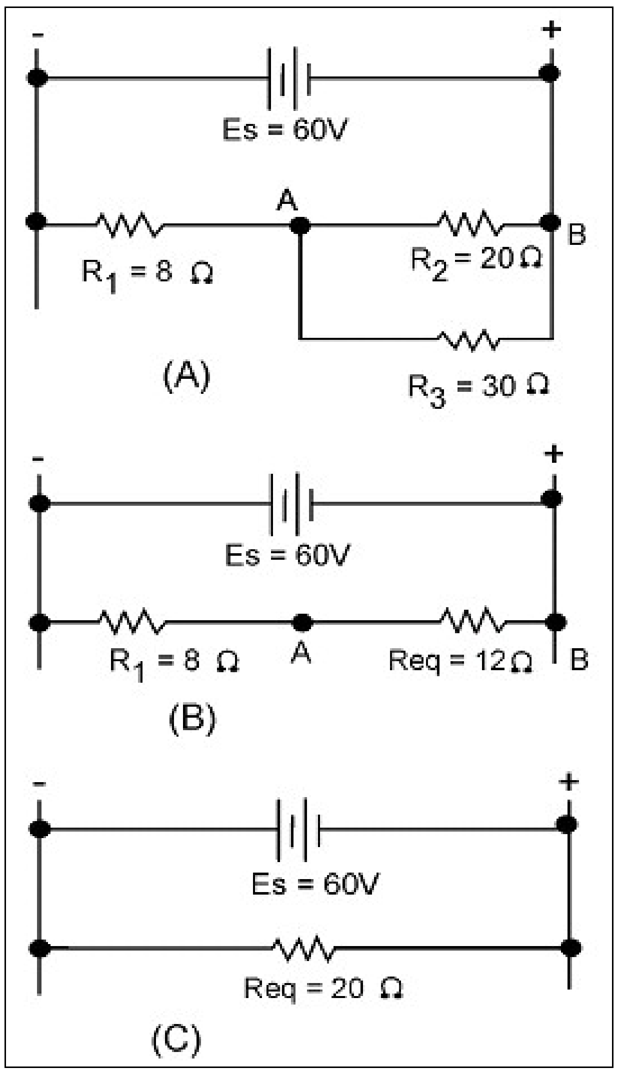

Figure 3-36. Simple Series-Parallel Circuit

3-104. See Figure 3-36, view B, to find the voltage dropped across R_1, R_2, and R_3. $R_{2,3}$ represents the parallel network of R_2 and R_3. Since the voltage across each branch of a parallel circuit is equal, the voltage across $R_{2,3}$ will be the same across R_2 and R_3.

Given:

I_T	=	3 amps (current through each part of a series circuit equals total current)
R_1	=	8 ohms
$R_{2,3}$	=	12 ohms

Solution:

E_1	=	$I_1 \times R_1$
E_1	=	3 amps x 8 ohms
E_1	=	24 volts
E_2	=	$E_3 = E_{2,3}$
$E_{2,3}$	=	$I_T \times R_{2,3}$
$E_{2,3}$	=	3 amps x 12 ohms
$E_{2,3}$	=	36 volts
E_2	=	36 volts
E_3	=	36 volts

To find power used by R_1—

Given:

E_1	=	24 volts
I_T	=	3 amps

Solution:

P_1	=	$E_1 \times R_T$
P_1	=	24 volts x 3 amps
P_1	=	72 watts

To find the current through R_2 and R_3, refer to the original circuit (see Figure 3-36, view A). E_2 and E_3 are known from previous calculation.

Given:

E_2	=	36 volts
E_3	=	36 volts
R_2	=	20 ohms
R_3	=	30 ohms

Solution:

$I_2 = \frac{E_2}{R_2}$ (Ohm's law)

$I_2 = \frac{36 \text{ volts}}{20 \text{ ohms}}$

$I_2 = 1.8$ amps

$I_3 = \frac{E_3}{R_3}$

$I_3 = \frac{36 \text{ volts}}{30 \text{ ohms}}$

$I_3 = 1.2$ amps

To find power used by R_2 and R_3, using values from previous calculations—

Given:

$E_2 = 36$ volts

$E_3 = 36$ volts

$I_2 = 1.8$ amps

$I_3 = 1.2$ amps

Solution:

$P_2 = E_2 \times I_2$

$P_2 = 36$ volts x 1.8 amps

$P_2 = 64.8$ watts

$P_3 = E_3 \times I_3$

$P_3 = 36$ volts x 1.2 amps

$P_3 = 43.2$ watts

3-105. After computing all the currents and voltages of Figure 3-36, a complete description of the operation of the circuit can be made. The total current of 3 amperes leaves the negative terminal of the battery and flows through the 8-ohm resistor (R_1). In so doing, a voltage drop of 24 volts occurs across resistor R_1. At point A, this 3-ampere current divides into two currents. Of the total current, 1.8 amperes flows through the 20-ohm resistor. The remaining current of 1.2 amperes flows from point A and down through the 30-ohm resistor to point B. This current produces a voltage drop of 36 volts across the 30-ohm resistor (notice that the voltage drops across the 20- and 30-ohm resistors are the same). The two branch currents of 1.8 and 1.2 amperes combine at node B and the total current of 3 amperes flows back to the source. The action of the circuit has been completely described with the exception of power consumed, which could be described using the values previously computed.

3-106. The series-parallel network is not difficult to solve. The key to its solution lies in knowing the order to apply the steps of the solution. First look at the circuit. From this observation, determine the type of circuit, what is known, and what must be determined.

DIRECT CURRENT

Questions

1. What does a schematic diagram show?
2. In Ohm's equation I = E/R, what can you determine if you know any of the other two quantities?
3. What is power?
4. What is the basic unit of power?
5. What are the four most important electrical quantities?
6. What does the power rating indicate?
7. When are wirewound resistors used?
8. What term applies to the power that is used by electrical devices which is converted from one form of energy to another?
9. What is the name of the circuit that contains only one path for current flow?
10. In any series circuit, the sum of the resistor voltage drops must equal to what?
11. What determines the value of the voltage dropped by a resistor?
12. What should be considered when applying Ohm's law to a series circuit?
13. What is an open circuit?
14. What is a short circuit?
15. What cannot be measured directly with a meter?
16. What is transferred from the source to the load when the resistance of the load equals the internal resistance of the source?
17. How many paths for current does the series circuit have?
18. How many paths for current are in a series circuit?
19. What is a node?
20. What values are used to calculate the total resistance of a circuit?
21. What is the only formula that can be used to determine the equivalent resistance in any combination of parallel resistances?
22. What is the name of the process by which a complex circuit consisting of resistances can be redrawn (reduced) to a basic equivalent circuit containing the voltage source and a single resistor representing total resistance?
23. What is the name of the basic technique used for solving DC combination-circuit problems?

Chapter 4

Batteries

A battery consists of a number of cells assembled in a common container and connected together to function as a source of electrical power. Batteries are widely used as sources of DC electrical energy in automobiles, boats, aircraft, shops, portable electronic equipment, and lighting equipment. In some instances, batteries are used as the only source of power. In others, they are used as a secondary or emergency power source. This chapter introduces the basic theory, physical characteristics, and maintenance requirements of batteries. It also includes a section on battery safety. The batteries discussed are representative of the many models and types used in the Army.

BATTERY COMPONENTS

4-1. A battery consists of a number of cells assembled in a common container. Connected together, they function as a source of electrical power.

THE CELL

4-2. A cell is a device that transforms chemical energy into electrical energy. Figure 4-1 shows the simplest cell, known as a galvanic or voltaic cell. It consists of a piece of carbon (C) and a piece of zinc (Zn) suspended in a jar that contains a sulfuric acid solution (H_2SO_4), called the electrolyte.

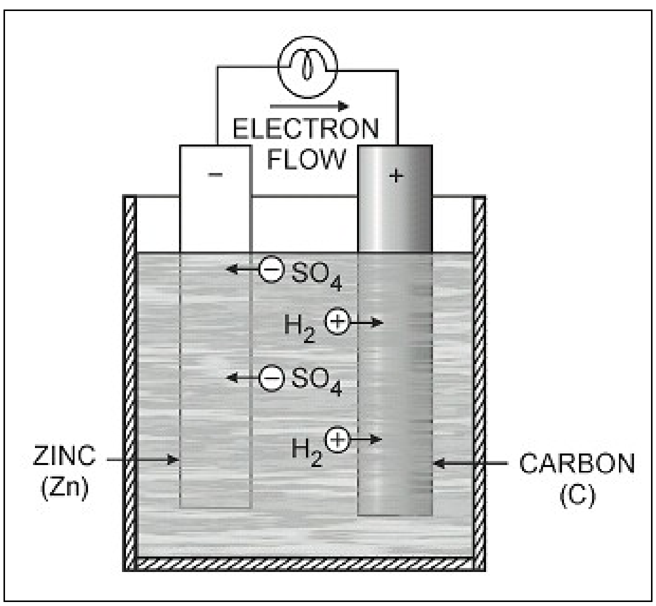

Figure 4-1. Simple Voltaic or Galvanic Cell

4-3. The cell is the fundamental unit of the battery. A simple cell consists of two electrodes placed in a container that holds the electrolyte. In some cells, the container acts as one of the electrodes and is acted upon by the electrolyte.

ELECTRODES

4-4. The electrodes are the conductors by which the current leaves or returns to the electrolyte. In the simple cell, they are carbon and zinc strips placed in the electrolyte. In the dry cell (see Figure 4-2), they are the carbon rod in the center and zinc container in which the cell is assembled.

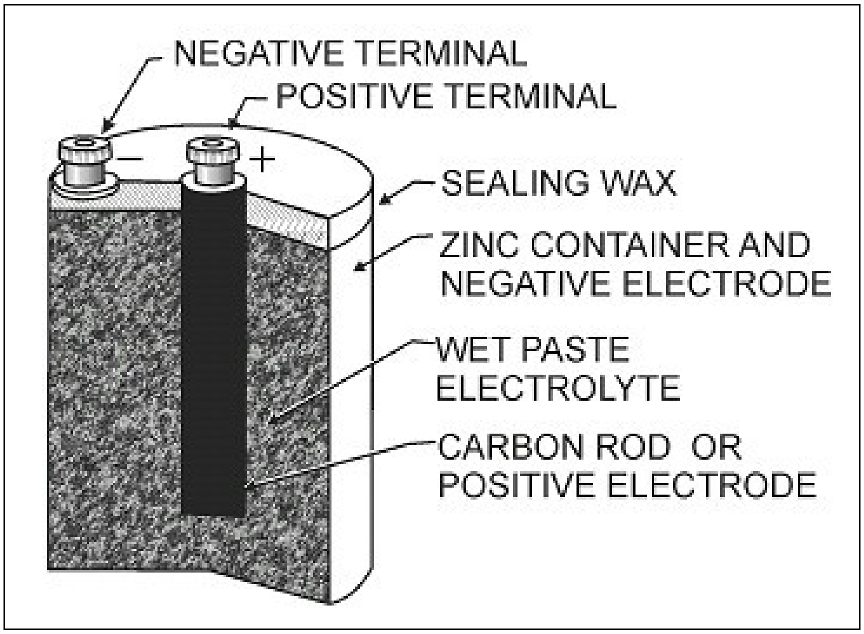

Figure 4-2. Dry Cell Cross-Sectional View

ELECTROLYTE

4-5. The electrolyte is the solution that reacts with the electrodes. The electrolyte provides a path for electron flow. It may be a salt, an acid, or an alkaline solution. In the simple galvanic cell the electrolyte is a liquid. In the dry cell the electrolyte is a paste.

CONTAINER

4-6. The container provides a means of holding (containing) the electrolyte. It is also used to mount the electrodes. The container may be constructed of one of many different materials. In the voltaic cell, the container must be constructed of a material that will not be acted upon by the electrolyte.

PRIMARY AND SECONDARY CELLS

4-7. According to the kind of electrochemical process used within the battery to produce electric energy, batteries may be classified as either primary or secondary cells. Primary batteries produce energy until the reactants (starting materials) of the electrochemical reaction are completely used up and then the battery cannot be used again. The electrochemical reaction in secondary (also called storage) batteries is not permanent in this way, because the reaction can be reversed using a flow of electrons to convert the products of the reaction back into the original reactants. The process of energy conversion may then take place again.

PRIMARY CELL

4-8. In a primary cell, the chemical action eats away one of the electrodes, usually the negative electrode. When this happens, the electrode must be replaced or the cell must be discarded. In a galvanic-type cell, the zinc electrode and the liquid electrolyte are usually replaced. It is usually cheaper to buy a new dry cell than it is to repair it.

SECONDARY CELL

4-9. In a secondary cell, the electrodes and electrolyte are altered by the chemical action that takes place when the cell delivers current. A secondary cell may be restored to its original condition by forcing an electric current through it in the direction opposite to that of discharge. The automobile storage battery is a common example of a secondary cell.

ELECTROCHEMICAL ACTION

4-10. When a load (a device that consumes electrical power) is connected to the electrodes of a charged cell, electrons will move from the cathode (negative electrode) toward the anode (positive electrode). The conversion of the cell's chemical energy to a productive electrical energy is called electrochemical action.

4-11. The voltage across the electrodes depends on the materials the electrodes are made of and the composition of the electrolyte. The current a cell delivers depends on the resistance of the entire circuit, including the cell itself. The internal resistance of the cell depends on the size of the electrodes, the distance between them in the electrolyte, and the resistance of the electrolyte. The larger the electrodes and the nearer their proximity in the electrolyte (without touching), the lower the internal resistance of the cell. The lower the internal cell resistance, the smaller the voltage loss within the cell while delivering current.

PRIMARY CELL CHEMISTRY

4-12. The following chemical reaction takes place when a current flows through a primary cell having carbon and zinc electrodes and a diluted solution of sulfuric acid and water (combined to form the electrolyte). The current flow through the load is the movement of electrons from the negative electrode (zinc) of the cell to the positive electrode (carbon). This results in fewer electrons in the zinc and an excess of electrons in the carbon. Figure 4-1 shows the hydrogen ions (H_2) from the sulfuric acid being attracted to the carbon electrode. Since the hydrogen ions are positively charged, they are attracted to the negative charge on the carbon electrode. The excess of electrons causes this negative charge. The zinc electrode has a positive charge because it has lost electrons to the carbon electrode. This positive charge attracts the negative ions (SO_4) from the sulfuric acid. The negative ions combine with the zinc to form zinc sulfate. This action causes the zinc electrode to be eaten away. Zinc sulfate is a grayish-white substance that is sometimes seen on the battery post of an automobile battery.

4-13. The process of the zinc being eaten away and the sulfuric acid changing to hydrogen and zinc sulfate causes the cell to discharge. When the zinc is used up, the voltage of the cell is reduced to zero.

4-14. In Figure 4-1, the zinc electrode is labeled negative and the carbon electrode is labeled positive. This represents the current flow outside the cell from negative to positive.

4-15. The zinc combines with the sulfuric acid to form zinc sulfate and hydrogen. The zinc sulfate dissolves in the electrolyte (sulfuric acid and water) and the hydrogen appears as gas bubbles around the carbon electrode. As current continues to flow, the zinc gradually dissolves and the solution changes to zinc sulfate and water. The carbon electrode does not have anything to do with the chemical changes taking place but simply provides a return path for the current.

SECONDARY CELL CHEMISTRY

4-16. The lead-acid cell (see Figure 4-3) is an example of a secondary cell. It uses sponge lead as the cathode and lead peroxide as the anode. This lead-acid cell is used to explain the general chemistry of the secondary cell. The materials that make up other types of secondary cells are different, but the chemical action is basically the same.

4-17. Figure 4-3, view A, shows a fully charged, lead-acid secondary cell. The cathode is pure sponge lead. The anode is pure lead peroxide. The electrolyte is a mixture of sulfuric acid and water.

4-18. Figure 4-3, view B, shows the secondary cell discharging. A load is connected between the cathode and anode. Current flows negative to positive. This current flow creates the same process found in the primary cell with the following exceptions. In the primary cell, the zinc cathode was eaten away by the sulfuric acid. In the secondary cell, the sponge-like construction of the cathode retains the lead sulfate formed by the chemical action of the sulfuric acid and the lead. In the primary cell, the carbon anode was not chemically acted on by the sulfuric acid. In the secondary cell, the lead peroxide anode is chemically changed to lead sulfate by the sulfuric acid.

4-19. Figure 4-3, view C, shows a fully discharged cell. The anode and cathode retain some lead peroxide and sponge lead, but the amounts of lead sulfate in each is maximum. The electrolyte has a minimum amount of sulfuric acid. With this condition, no further chemical action can take place within the cell.

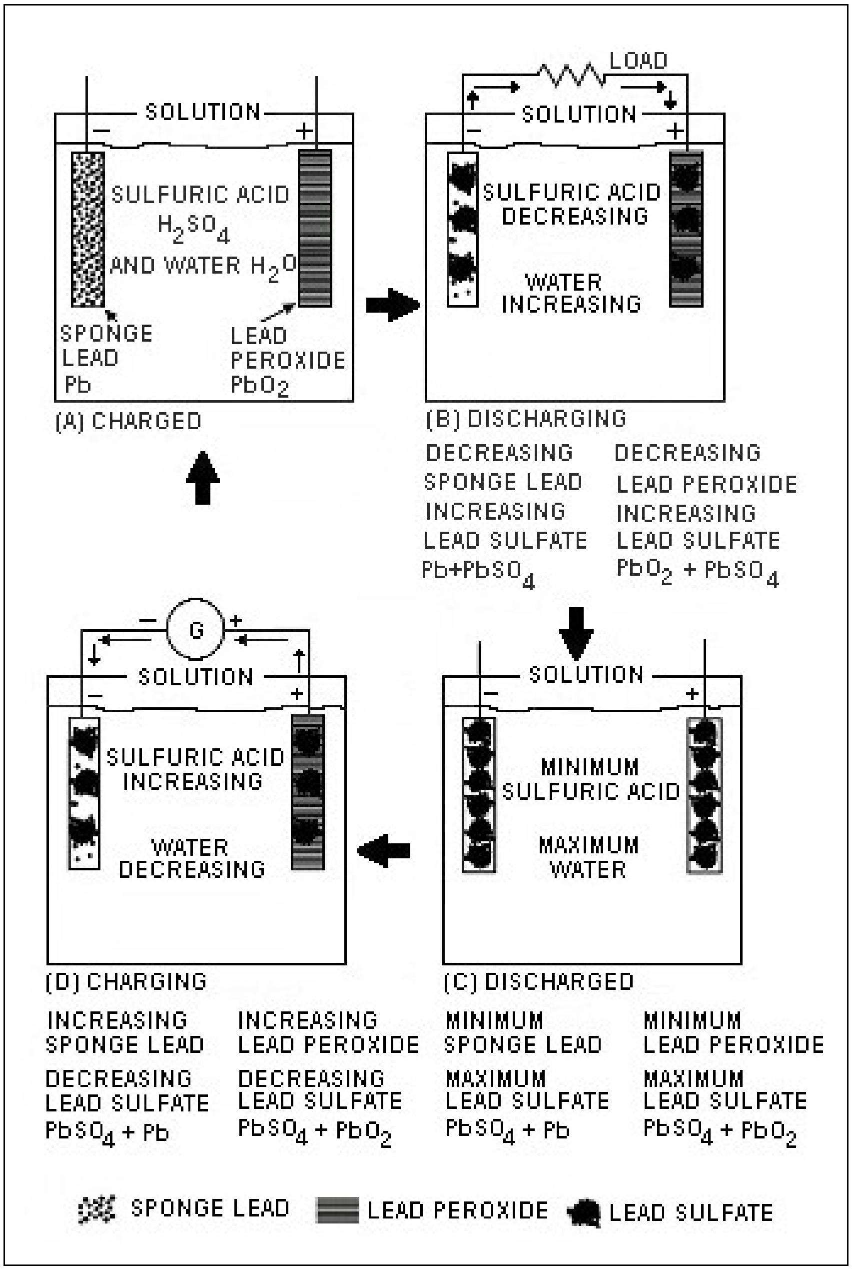

Figure 4-3. Secondary Cell

4-20. A secondary cell can be recharged. This is the process of reversing the chemical action that occurs as the cell discharges. To recharge the cell, a voltage source (such as a generator) is connected to the cell (see Figure 4-3, view D). The negative terminal of the voltage source is connected to the cathode of the cell and the positive terminal of the voltage source is connected to the anode of the cell. This arrangement chemically changes the lead sulfate back to sponge lead in the cathode, lead peroxide in the anode, and sulfuric acid in the electrolyte. After the entire lead sulfate is chemically changed, the cell is fully charged (see Figure 4-3, view A). The discharge-charge cycle may then be repeated.

POLARIZATION OF THE CELL

4-21. The chemical action that occurs in the cell while the current is flowing causes hydrogen bubbles to form on the surface of the anode. This action is called polarization. Some hydrogen bubbles rise to the surface of the electrolyte and escape into the air. Some remain on the surface of the anode. If enough bubbles remain around the anode, the bubbles form a barrier that increases internal resistance. When the internal resistance of the cell increases, the output current decreases and the voltage of the cell also decreases.

4-22. A cell that is heavily polarized has no useful output. There are several methods to prevent polarization or to depolarize the cell. One method uses a vent on the cell to let the hydrogen escape into the air. A disadvantage of this method is that hydrogen is not available to reform into the electrolyte during recharging. This problem is solved by adding water to the electrolyte (such as in an automobile battery). A second method uses a material rich in oxygen (such as manganese dioxide) to supply free oxygen to combine with the hydrogen and form water. A third method uses a material (such as calcium) to absorb the hydrogen. The calcium releases hydrogen during the charging process. All three methods remove enough hydrogen so that the cell is practically free from polarization.

LOCAL ACTION

4-23. When the external circuit is removed, the current ceases to flow, and theoretically, all chemical action within the cell stops. However, commercial zinc contains many impurities (such as iron, carbon, lead, and arsenic). These impurities form many small electrical cells within the zinc electrode in which current flows between the zinc and its impurities. Therefore, the chemical action continues even though the cell itself is not connected to a load. Removing and controlling impurities in the cell greatly increases the life of the battery.

TYPES OF CELLS

4-24. The development of new and different types of cells in the past decade has been so rapid that it is almost impossible to have a complete knowledge of all the various types. A few recent developments are the silver-zinc, nickel-zinc, nickel-cadmium, silver-cadmium, organic, inorganic, and mercury cells.

PRIMARY DRY CELL

4-25. The dry cell is the most popular type of primary cell. It is ideal for simple applications where an inexpensive and noncritical source of electricity is all that is needed. The dry cell is not actually dry. The electrolyte is not in a liquid state, but it is a moist paste. If it should become totally dry, it would no longer be able to transform chemical energy to electrical energy.

4-26. Figure 4-4 shows the construction of a common type of dry cell. The internal parts of the cell are located in a cylindrical zinc container. This zinc container serves as the negative electrode (cathode) of the cell. The container is lined with a nonconducting material (such as blotting paper) to separate the zinc from the paste. A carbon electrode in the center serves as the positive terminal (anode) of the cell. The paste is a mixture of several substances (such as ammonium chloride, powdered coke, ground carbon, manganese dioxide, zinc chloride, graphite, and water). It is packed in the space between the anode and the blotting paper. The paste also serves to hold the anode rigid in the center of the cell. When the paste is packed in the cell, a small space is left at the top for expansion of the electrolytic paste caused by the depolarization action. The cell is than sealed with a cardboard or plastic seal.

4-27. Since the zinc container is the cathode, it must be protected with some insulating material to be electrically isolated. Therefore, it is common practice for the manufacturer to enclose the cells in the cardboard and metal containers.

4-28. The dry cell (see Figure 4-4) is basically the same as the simple voltaic cell (wet cell) as far as its internal chemical action is concerned. The action of the water and the ammonium chloride in the paste, together with the zinc and carbon electrodes, produces the voltage of the cell. Manganese dioxide is added to reduce polarization when current flows and zinc chloride reduces local action when the cell is not being used.

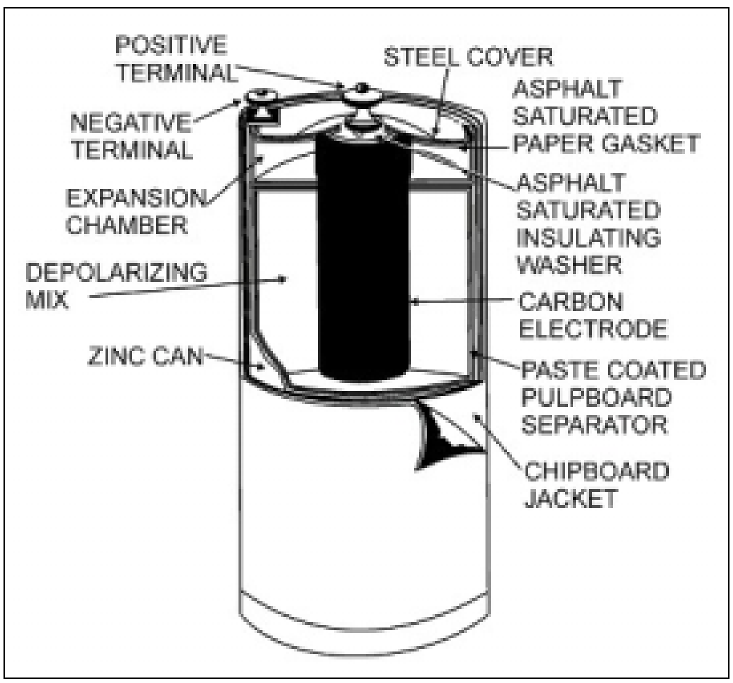

Figure 4-4. Cutaway View of the General-Purpose Dry Cell

4-29. A cell that is not being used (sitting on the shelf) will gradually deteriorate because of slow internal chemical changes (local action). This deterioration is usually very slow if cells are properly stored. If unused cells are stored in a cool place, their shelf life will be greatly increased. Therefore, to reduce deterioration, they should be stored in refrigerated spaces.

4-30. The blotting paper (paste-coated pulpboard separator) (see Figure 4-4) serves two purposes:

- It keeps the paste from actually contacting the zinc container.
- It lets the electrolyte from the paste to slowly filter through to the zinc.

The cell is sealed at the top to keep air from entering and drying the electrolyte. Care should be taken to prevent breaking this seal.

SECONDARY WET CELLS

4-31. Secondary cells are sometimes known as wet cells. The following are the four basic types of wet cells:

- Lead-acid.
- Nickel-cadmium.
- Silver-zinc.
- Silver-cadmium.

Different combinations of materials are used to form the electrolyte, cathode, and anode of different cells. These combinations provide the cells with different qualities for many varied applications.

4-32. **Lead-acid cell**. The lead-acid cell is the most widely used secondary cell. The previous explanation of the secondary cell describes how the lead-acid cell provides electrical power. The electrochemical action section in this chapter describes the discharging and charging action for the lead-acid cell. The lead-acid cell has an anode of lead peroxide, a cathode of sponge lead, and an electrolyte of sulfuric acid and water.

4-33. **Nickel-cadmium cell**. The nickel-cadmium (or NICAD) cell is far superior to the lead-acid cell. In comparison to lead-acid cells, these cells generally require less maintenance throughout their service life regarding the addition of electrolyte or water. The major difference between the nickel-cadmium cell and the lead-acid cell is the material used in the cathode, anode, and electrolyte. In the nickel-cadmium cell, the cathode is cadmium hydroxide; the anode is nickel hydroxide; and the electrolyte is potassium hydroxide and water.

4-34. The nickel-cadmium and lead-acid cells have capacities that are comparable at normal discharge rates. However, at higher discharge rates, the nickel-cadmium cell can deliver a large amount of power. The nickel-cadmium cell can also—

- Be charged in a shorter time.
- Stay idle longer in any state of charge and keep a full charge when stored for a longer period of time.
- Be charged and discharged any number of times without any appreciable damage.

Nickel-cadmium cells, because of their superior capabilities, are used extensively in many military applications that require a cell with a high discharge rate. A good example is in the Theater Support Vessel storage battery.

4-35. **Silver-zinc cell**. The silver-zinc cell is used extensively to power emergency equipment. However, it is relatively expensive and can be charged and discharged fewer times than other types of cells. When compared to lead-acid or nickel-cadmium cells, these disadvantages are outweighed by its light weight, small size, and good electrical capacity of the silver-zinc cell. The silver-zinc cell uses the same electrolyte (potassium hydroxide and water) as the nickel-cadmium cell. However, the anode and cathode differ. The anode is made of silver oxide and the cathode is made of zinc.

4-36. **Silver-cadmium cell**. The silver-cadmium cell is a recent development for use in storage batteries. This type of cell combines some of the better features of the nickel-cadmium and silver-zinc cells. It has more than twice the shelf life of the silver-zinc cell and can be recharged many more times. The disadvantages of the silver-cadmium cell are high cost and low voltage production. The electrolyte of the silver-cadmium cell is potassium hydroxide and water as in the nickel-cadmium and silver-zinc cells. The anode is silver oxide as in the silver-zinc cell and the cathode is cadmium hydroxide as in the nickel-cadmium cell.

BATTERIES AS POWER SOURCES

4-37. A battery is a voltage source that uses chemical action to produce a voltage. The term "battery" is often applied to a single cell (such as the flashlight battery). In a flashlight that uses a battery of 1.5 volts, the battery is a single cell. The flashlight that is operated by 6 volts uses four cells in a single case. Cells can be combined in series or in parallel.

4-38. In many cases, a battery-powered device may require more electrical energy than one cell can provide. The device may require a higher voltage or more current, or, in some cases, both. To meet the higher requirements, a sufficient number of cells must be combined or interconnected. Cells connected in series provide a higher voltage while cells connected in parallel provide a higher current capacity.

SERIES-CONNECTED CELLS

4-39. Assume that a load requires a power supply of 6 volts and a current capacity of 1/8 ampere. Since a single cell normally supplies a voltage of only 1.5 volts, more than one cell is needed. To obtain the higher voltage, the cells are connected in series (see Figure 4-5, view A). Figure 4-5, view B is a schematic representation of the circuit shown in

Figure 4-5, view A. The load is shown by the lamp symbol and the battery is indicated by one long and one short line per cell.

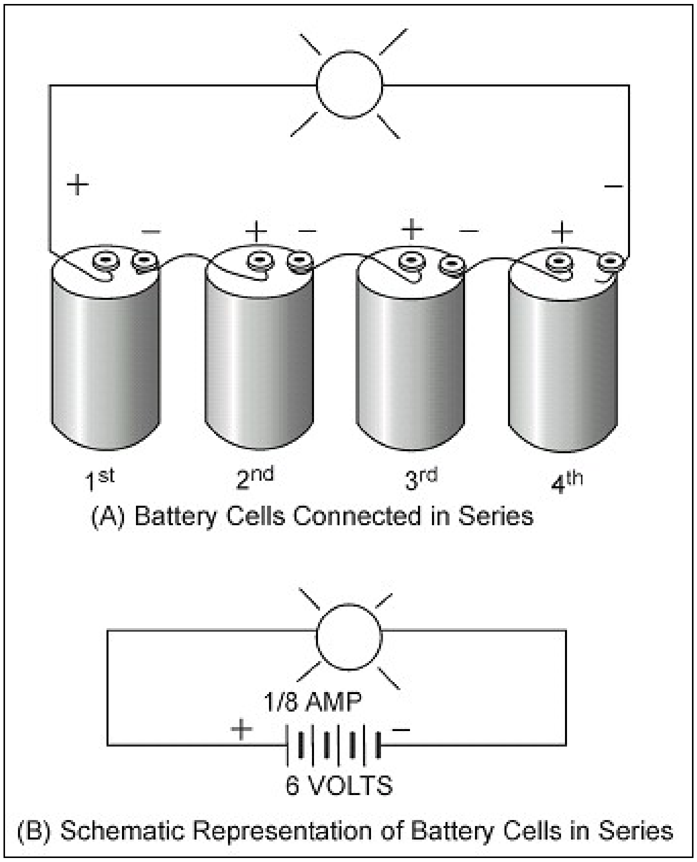

Figure 4-5. Series-Connected Cells

4-40. In a series hookup, the negative electrode (cathode) of the first cell is connected to the positive electrode (anode) of the second cell, the negative electrode of the second cell to the positive of the third cell, and so on. The positive electrode of the first cell and negative electrode of the last cell then serve as the terminals of the battery. Therefore, the voltage is 1.5 volts for each cell in the series line. There are four cells, so the output terminal voltage is 1.5 x 4 or 6 volts. When connected to the load, 1/8 ampere flows through the load and each cell of the battery. This is within the capacity of each cell. Therefore, only four series-connected cells are needed to supply this particular load.

WARNING

When connecting cells in series, there MUST ALWAYS be two unconnected terminals remaining. These two terminals must be connected to each side of a load. NEVER connect the final two remaining terminals together unless a load is placed between them. Physical harm or equipment damage will result.

PARALLEL-CONNECTED CELLS

4-41. Assume an electrical load requires only 1.5 volts but will require 1/2 ampere of current (also assume that a single cell will supply only 1/8 ampere). To meet this requirement, the cells are connected in parallel (see Figure 4-6, view A). The cells are schematically represented in Figure 4-6, view B. In a parallel connection, all positive cell electrodes are connected to one line and all negative electrodes are connected to the other. No more than one cell is connected between the lines at any one point so the voltage between the lines is the same as that of one cell, or 1.5 volts. However, each cell may contribute its maximum allowable current of 1/8 ampere to the line. There are four cells, so the total line current is 1/8 x 4, or 1/2 ampere. In this case, four cells in parallel have enough capacity to supply a load requiring 1/2 ampere at 1.5 volts.

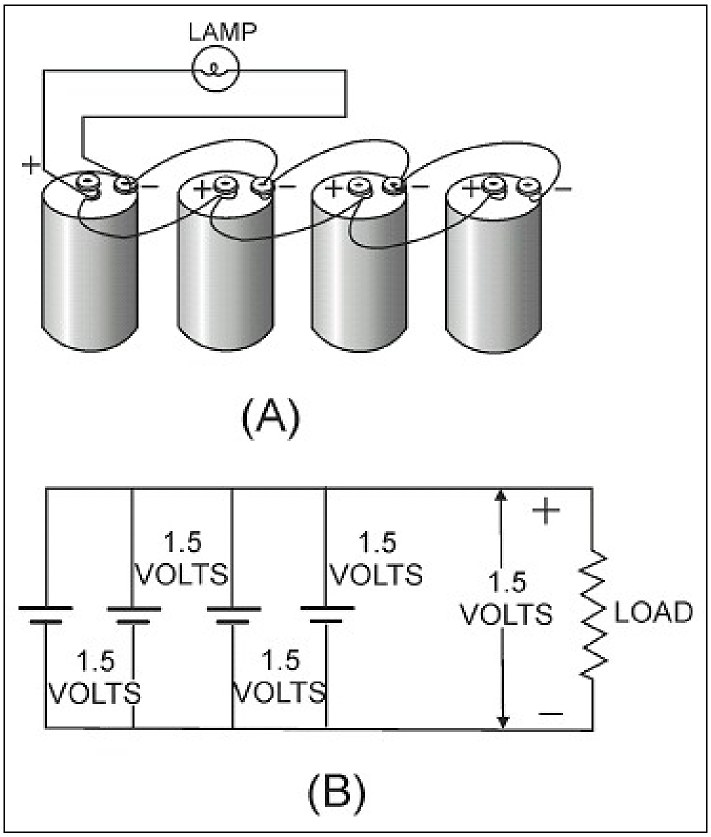

Figure 4-6. Parallel-Connected Cells

BATTERY CONSTRUCTION

4-42. Secondary cell batteries are constructed using the various secondary cells already described. The lead-acid battery, one of the most common batteries, will be used to explain battery construction. The nickel-cadmium battery, which is being used with increasing frequency, will also be discussed.

4-43. Figure 4-7 shows the makeup of a lead-acid battery. The container houses the separate cells. Most containers are hard rubber, plastic, or some other material that is resistant to the electrolyte and mechanical shock. The containers can also withstand extreme temperatures. The container (battery case) is vented through vent plugs to allow the gases that form within the cells to escape. The plates in the battery are the cathode and anodes. In Figure 4-8, the negative plate group is the cathode of the individual cells and the positive plate group is the anode. The plates are interlaced with a terminal attached to each plate group. The terminals of the individual cells are connected together by link connectors (see Figure 4-7). The cells are connected in series in the battery and the positive terminal of the battery. The negative terminal of the opposite end cell becomes the negative terminal of the battery.

4-44. The terminals of a lead-acid battery are usually identified from one another by their size and markings. The positive terminal, marked (+), is sometimes colored red and is physically larger than the negative terminal, marked (-). The individual cells of the lead-acid battery are not replaceable. Therefore, if one cell fails, the battery must be replaced.

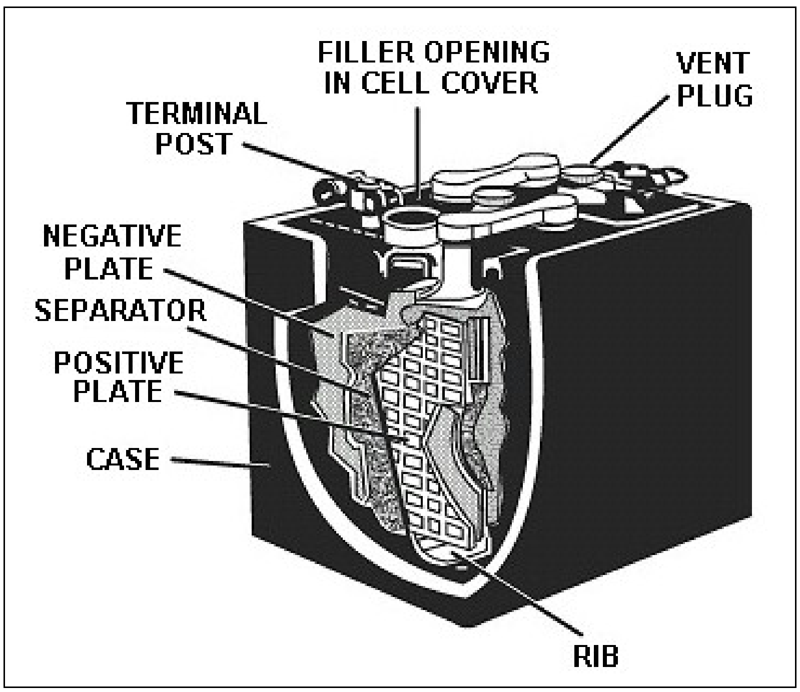

Figure 4-7. Lead-Acid Construction

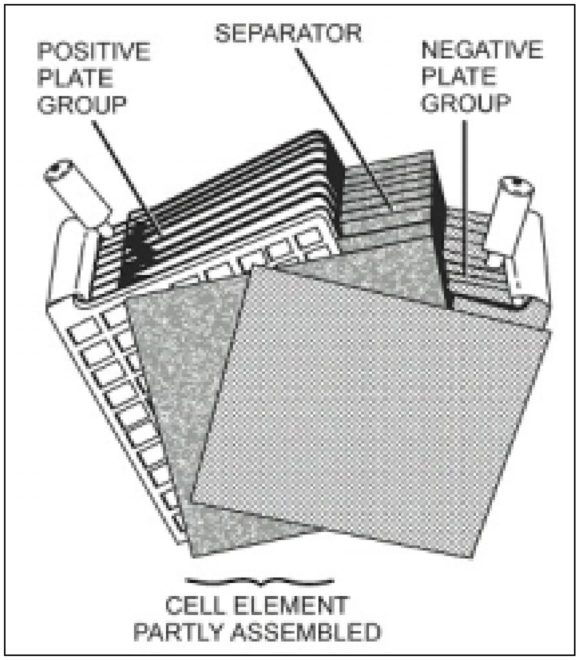

Figure 4-8. Lead-Acid Battery Plate Arrangement

4-45. The nickel-cadmium battery is similar in construction to the lead-acid battery, except that it has individual cells that can be replaced. Figure 4-9 shows the cell of the nickel-cadmium battery.

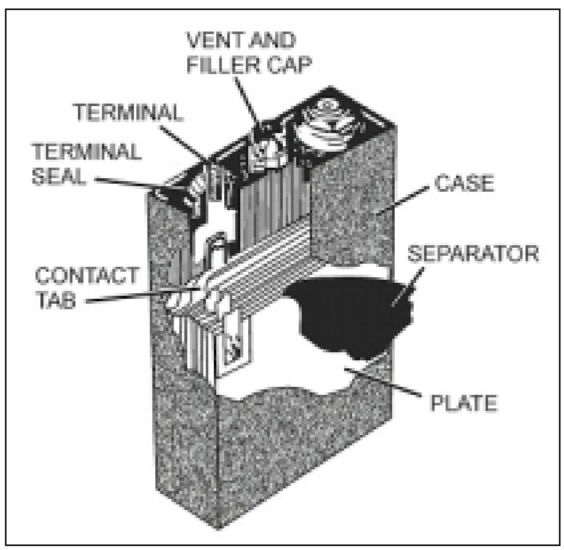

Figure 4-9. Nickel-Cadmium Cell

4-46. The construction of secondary cell batteries is so similar that it is difficult to distinguish the type of battery by simply looking at it. The type of battery must be known to properly check or recharge the battery. Each battery should have a nameplate that gives a description of its type and electrical characteristics.

BATTERY MAINTENANCE

4-47. The transportation field relies on the battery's ability to store electrical power until such time as the power is needed. Army watercraft personnel use the battery not only for diesel starting but also as an emergency source of power during an electrical casualty. The general information below concerns the maintenance of secondary-cell batteries, in particular the lead-acid battery. Refer to the appropriate TM before engaging in any other battery maintenance.

LEAK TEST

4-48. Cleanliness of the lead-acid battery is a primary concern because moisture and dirt are conductors. Batteries that are allowed to gas excessively add additional conductive liquid to the top and sides of the battery. Damp battery surfaces retain conductive dirt and debris.

4-49. A simple test, known as the leak test, provides a visual and authoritative assessment for battery cleanliness. Figure 4-10 illustrates the procedure described below.

- Select a DC voltage scale at or above battery voltage.
- Connect the negative meter lead to the negative battery post (the smaller battery post).
- Use the positive meter lead to probe the housing of the battery.
- Measure the voltage leaking across the two battery terminals using the multimeter.

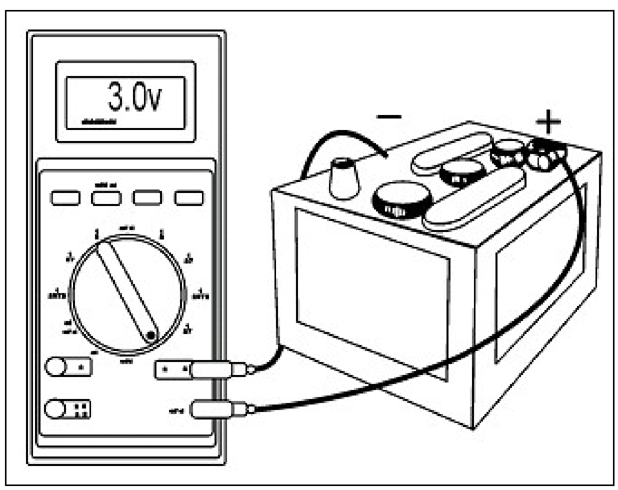

Figure 4-10. Leak Test

Note: Grease is not an acceptable battery terminal preservative. The heat from the battery compartment often melts the grease, which in turn covers the top and sides of the battery with a thin coating of lubricant. Dirt and dust adhere easily to this surface.

IDLE WINTER BATTERIES

4-50. Battery maintenance becomes even more critical during the winter months. The cold weather increases the already difficult task of starting diesel engines. Since the starter motor rotates slower than normal, less CEMF is developed and the current to the starter motor remains high. This increased current depletes the storage batteries rapidly. Problems are readily observed after extended winter weekends. Do the following to ensure the batteries are maintained at a high state of readiness:

- Always service and charge batteries thoroughly whenever the batteries are to enter an idle period. A discharged battery will freeze at about 18 degrees Fahrenheit. A frozen battery greatly increases the chance of a battery detonation. Detonation occurs during excessive charging or prolonged efforts to jump start equipment under these severe conditions.
- After the batteries are serviced and charged, disconnect the cables. Always disconnect the negative battery post first. Many small electrical problems in the starting or charging system can conduct current and discharge the batteries. When the equipment is operated regularly, small electrical deficiencies may not be noted. However, these electrical deficiencies become apparent when equipment is left idle, even for a short time.

BATTERY MAINTENANCE TOOLS

4-51. The most acceptable manner to clean battery terminals and clamps is to use the cutter or straight-edge type of battery terminal and clamp cleaner. Wire-type battery terminal and clamp cleaners can damage the battery posts and clamps. Figure 4-11 shows the physical differences between the two cleaners.

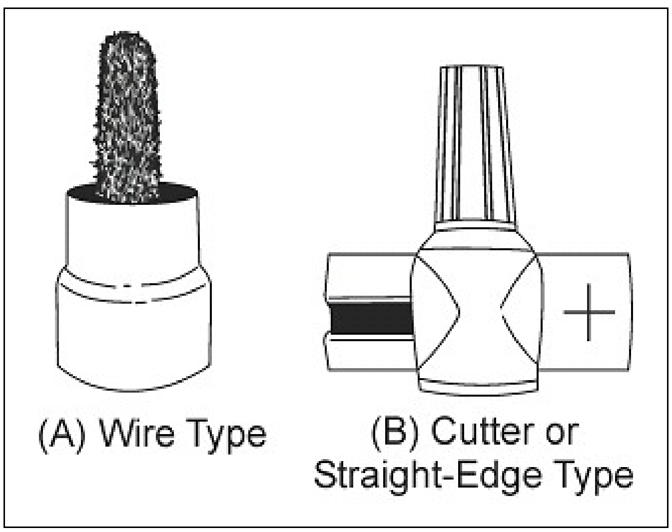

Figure 4-11. Battery Terminal and Clamp Cleaners

4-52. Figure 4-12, view A, shows a battery terminal in need of cleaning. The main concern for cleaning is to provide a large, clean contact surface area for the unimpeded flow of current. In Figure 4-12, view B, a cutter-type terminal cleaner is used. The cutter-type cleaner ensures a concentric post surface uniform in contact area. The cutter leaves some of the surface area soiled and dull because it is designed to maintain the original taper of both the post and the clamp. The cutter can remove only a small amount of the outer post surface area each time. The low pitted areas grow smaller in dimension as the tool is used. Figure 4-12, view C, shows the battery terminal fully cleaned with the cutter-type terminal cleaner.

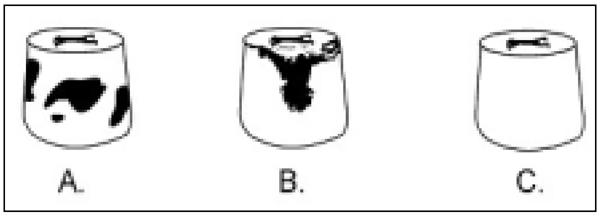

Figure 4-12. Cleaning a Dirty Battery Terminal

4-53. When the inside of the terminal clamp is cleaned with the cutter-type cleaner, a similar condition results (see Figure 4-13). Pits are visible and continually reduced in size. The cutting can continue until a uniform and properly tapered clean surface results.

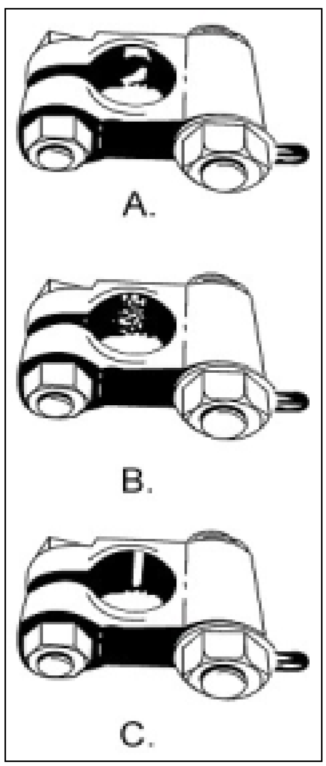

Figure 4-13. Cleaning a Dirty Battery Clamp

4-54. The wire-type cleaner cannot restore the surface of the post or clamp. It will clean the entire area, but it cannot restore any irregularities in the surfaces. It actually increases the surface distortions. Pits get bigger and the necessary contact surface area is decreased. The original taper is also lost. The surface area is eventually reduced to a point where excessive heat from current flow can melt the post and clamp. A spark may also result, detonating the battery. As Figure 4-14 shows, reduced contact area equals increased heating.

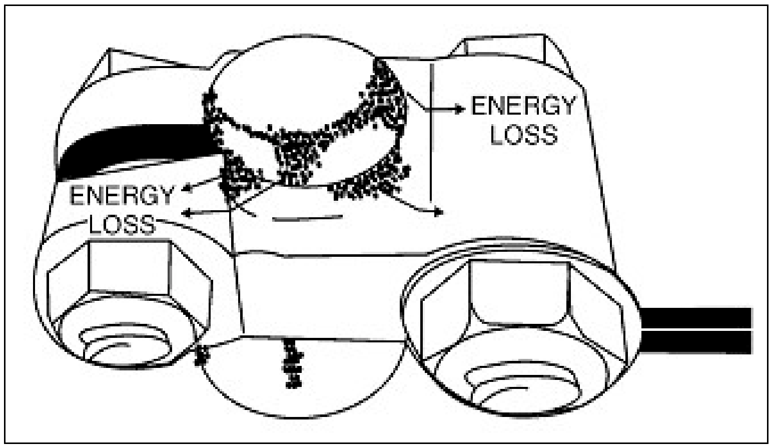

Figure 4-14. Reduced Contact Area Equals Increased Heating

4-55. Use a battery terminal clamp puller to remove battery clamps from the terminals. Prying the clamp from the terminal with a screwdriver will damage the terminal.

BATTERY LOG

4-56. Keep weekly specific gravity readings and overall battery bank voltage readings in a battery logbook. This will provide an accurate and complete operational status of each battery to forecast any cells that are becoming deficient. Figure 4-15 is an example of a battery logbook.

THE HYDROMETER

4-57. A hydrometer (see Figure 4-16) is the instrument that measures the amount of active ingredients in the electrolyte of the battery. The hydrometer also measures the specific gravity of the electrolyte. Specific gravity is the ratio of the weight of the electrolyte to the weight of the same volume of pure water. The active ingredient (such as sulfuric acid or potassium hydroxide) is heavier than water. Therefore, the more active ingredient there is in the electrolyte, the heavier the electrolyte will be. The heavier the electrolyte is, the higher the specific gravity will be.

4-58. The hydrometer is a glass syringe with a float inside. The float is a hollow glass tube weighted at one end and sealed at both ends. The float also has a scale calibrated in specific gravity marked on the side. The electrolyte to be tested is drawn into the hydrometer by using the suction bulb. Enough electrolyte should be drawn into the hydrometer so that the float will rise. However, the hydrometer should not be filled to the extent that the float rises into the suction bulb. Since the weight of the float is at its base, the float will rise to a point determined by the weight of the electrolyte. If the electrolyte contains a large concentration of active ingredient, the float will rise higher than if the electrolyte has a small concentration of active ingredient.

Date Serviced:

Battery No. 1:		**Battery No. 2:**	
Date Installed:		**Date Installed:**	
Specific Gravity Readings (negative to positive terminal)			
Cell 1: __________	**Cell 4:** __________	**Cell 1:** __________	**Cell 4:** __________
Cell 2: __________	**Cell 5:** __________	**Cell 2:** __________	**Cell 5:** __________
Cell 3: __________	**Cell 6:** __________	**Cell 3:** __________	**Cell 6:** __________
Battery No. 3:		**Battery No. 4:**	
Date Installed:		**Date Installed:**	
Cell 1: __________	**Cell 4:** __________	**Cell 1:** __________	**Cell 4:** __________
Cell 2: __________	**Cell 5:** __________	**Cell 2:** __________	**Cell 5:** __________
Cell 3: __________	**Cell 6:** __________	**Cell 3:** __________	**Cell 6:** __________
Battery No. 5:		**Battery No. 6:**	
Date Installed:		**Date Installed:**	
Cell 1: __________	**Cell 4:** __________	**Cell 1:** __________	**Cell 4:** __________
Cell 2: __________	**Cell 5:** __________	**Cell 2:** __________	**Cell 5:** __________
Cell 3: __________	**Cell 6:** __________	**Cell 3:** __________	**Cell 6:** __________

Figure 4-15. Battery Logbook

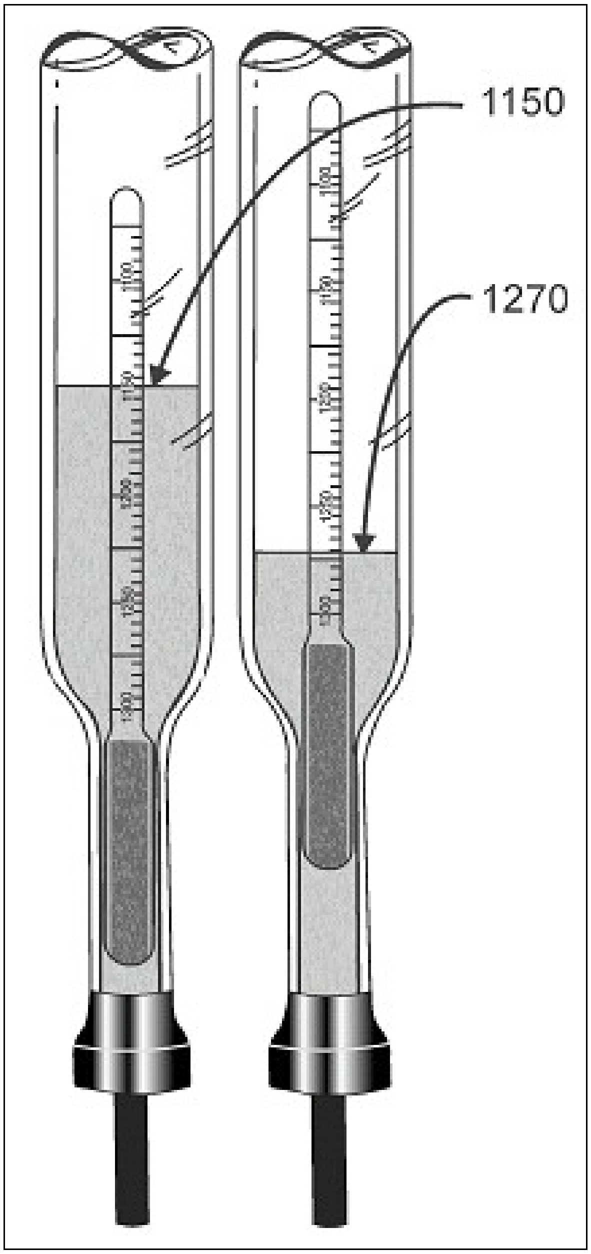

Figure 4-16. Hydrometer

WARNING

NEVER mix lead-acid and nickel-cadmium servicing tools together. NEVER store or transport nickel-cadmium and lead-acid batteries together. The combination of potassium hydroxide and sulfuric acid electrolytes generate a toxic gas that can kill!

4-59. To read the hydrometer, hold it in a vertical position and take the reading at the level of the electrolyte. Refer to the manufacturer's TM for battery specifications for the correct specific gravity ranges.

Note: Hydrometers should be flushed with fresh water after each use to prevent inaccurate readings. Storage battery hydrometers must not be used for any other purpose.

STATE OF CHARGE

4-60. Table 4-1 provides general guidance for the specific gravity of the lead-acid battery. Unless otherwise specified, the specific gravity readings between cells should be no greater that 30 points (.030). Any variations outside the specifications indicate an unsatisfactory condition. Therefore, the battery should be replaced.

WARNING

Care must be taken to prevent electrolytes from entering the eyes or from splashing on the skin.

Table 4-1. Specific Gravity of the Lead-Acid Battery

Specific Gravity Temperate Climates	Specific Gravity Tropical Climates	State of Charge
1.260 – 1.280	1.225	Fully charged
1.230 – 1.250	1.195	75 percent charged
1.200 – 1.220	1.165	50 percent charged
1.170 – 1.190	1.135	25 percent charged
1.110 – 1.130	1.075	Discharged

4-61. All testing of battery-powered equipment must be conducted with fully charged batteries. The manufacturer's technical data is based on the assumption that the power supply (batteries) is fully operational. Any deviation from the fully charged condition will change the testing results. If the batteries are not fully charged, the test results will be erroneous and inconclusive.

GASSING

4-62. When a battery is being charged, a portion of the energy breaks down the water in the electrolyte. Hydrogen is released at the negative plates and oxygen at the positive plates. These gases bubble up through the electrolyte and collect in the air space at the top of the cell. If violent gassing occurs when the battery is first placed on charge, the charging rate is too high. If the rate is not too high, steady gassing develops as the charging proceeds, indicating that the battery is nearing a fully charged condition.

4-63. Avoid excessive gassing. The by-products are hazardous and explosive. Any lost liquid from the battery cell is a combination of water and sulfuric acid. Since the specific gravity changes as the batteries increase in charge, it is impossible to anticipate the exact content of sulfuric acid removed from the cell. Every time the maintenance technician replenishes the cell with water, he is actually reducing the percentage of sulfuric acid within that cell. Eventually the chemical action will become deficient.

BATTERY CAPS

4-64. When taking hydrometer readings, avoid contaminating battery cap undersides by placing them upside down on the battery case. This will help keep debris from falling into the cell.

TROUBLESHOOTING BATTERY-POWERED SYSTEMS

4-65. Troubleshooting battery-powered systems can become complex. Unlike many mechanical systems, many electrical problems can be identified with a good initial inspection. Burned out electrical components have a distinctive electrical smell and charred wires and connections are readily identified. Once these areas are identified and corrected, further tests are needed to determine the reason for this condition.

4-66. Regularly check all connections (from the battery throughout the entire electrical system). All connections must be clean and tight. Army vessels operating in the salt air environment are especially prone to oxidation. All mobile units are prone to vibration. Vibration and oxidation together account for a large percentage of electrical malfunctions.

4-67. Any increase in resistance in the circuit reduces the current throughout the entire circuit. When current is reduced, the magnetic properties of the circuit are reduced. Current is a quantity of electrons (with their magnetic field) passing a point in the circuit in a period of time. With fewer electrons, there is a reduction in the magnetic properties available to the circuit components. With a reduction of electrons and their magnetic influence, motors, solenoids, and other electrical components will function irregularly. Some of the more obvious resistance increases are due to improper or dirty connections and corroded cable ends.

4-68. To understand how a small amount of additional resistance can reduce the capability of the electrical system, suppose that a resistance of 1 ohm exists in a poorly made connection in a diesel engine starting system. The 24-volt battery starting system normally provides 240 amps to a starting system with a resistance of .1 ohms. The 24 volts must now supply a starting system with 1.1 ohms resistance.

4-69. The additional 1-ohm resistance will consume power (power = amps x volts). The current will be reduced because the total resistance (R_T) is increased. The total amperage for the system is reduced as shown in the following equation:

$$I_T = \frac{E_T}{R_T}$$

Where:

E_T = 24 volts

R_T = 1.1 ohm

Solution:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{24 \text{ volts}}{1.1 \text{ ohm}}$$

$$I_T = 21.8 \text{ amps}$$

The starter cannot turn because the 240 amps required to turn the starter motor has been reduced to 21.8 amps.

BATTERY VOLTAGE

4-70. A fully charged lead-acid battery has 2.33 volts per cell. It is quite common for a 24-volt battery bank to actually have a voltage of 26.5 volts. The TM specifies the term “battery voltage” instead of 24 volts because the actual battery terminal voltage must be observed throughout the entire electrical testing procedure. The manufacturer is concerned with the actual battery bank voltage.

4-71. If a charged battery shows an extremely high voltage, it may be deficient. Individual 12-volt batteries should not exceed 15.5 volts and 6-volt batteries should not exceed 7.8 volts. If these voltages are exceeded, the battery is unsatisfactory and probably sulfated. These higher voltage values indicate only a superficial charge and are incapable of delivering the current capacity designed for the battery.

FULLY CHARGED BATTERIES

4-72. Test result standards are based on a fully functioning power supply. Always start troubleshooting the battery-powered electrical system at the batteries. The batteries must be fully operational and completely charged before testing any other electrical component. Charge the existing battery bank or substitute the batteries when other circuit components are suspect.

OTHER MAINTENANCE

4-73. Perform routine maintenance of batteries regularly. Check terminals periodically for cleanliness and good electrical connections. Inspect the battery case for cleanliness and evidence of damage. Check the level of electrolyte. If the electrolyte is low, add distilled water to bring the electrolyte to the proper level. A unit's higher authority normally determines maintenance procedures for batteries. Each command will have detailed procedures for battery care and maintenance.

SAFETY PRECAUTIONS WITH BATTERIES

4-74. Observe the following safety precautions when working with batteries:

- Handle all types of batteries with care.
- Never short the terminals of a battery.
- Use carrying straps when transporting batteries.
- Wear chemical splash-proof safety glasses when maintaining batteries.
- Wear protective clothing (such as a rubber apron and rubber gloves) when working with batteries. Electrolyte will destroy everyday clothing (such as the battle dress uniform).
- Do not permit smoking, electric sparks, or open flames near charging batteries.
- Take care to prevent spilling the electrolyte.
- Never install alkaline and lead-acid batteries in the same compartment.
- Do not exchange battery tools (including hydrometers) between lead-acid batteries and nickel-cadmium batteries.

4-75. In the event electrolyte is splashed or spilled on a surface (such as a deck or table) immediately dilute it with large quantities of water and clean it up. If electrolyte is spilled or splashed on the skin or eyes, immediately flush the area with large quantities of fresh water for a minimum of 15 minutes. If the electrolyte is in the eyes, be sure the upper and lower eyelids are pulled out sufficiently to allow the fresh water to flush under the eyelids. Notify, as soon as possible, the medical department of the type of electrolyte and the location of the accident.

CAPACITY AND RATING OF BATTERIES

4-76. The capacity of a battery is measured in ampere-hours. The ampere-hour capacity equals the product of the current in amperes and the time in hours during which the battery will supply this current. The ampere-hours capacity varies inversely with the discharge current. For example, a 400 ampere-hour battery will deliver 400 amperes for one hour or 100 amperes for four hours.

4-77. Storage batteries are rated according to their rate of discharge and ampere-hour capacity. Most batteries are rated according to a 20-hour rate of discharge. That is, if a fully charged battery is completely discharged during a 20-hour period, it is discharged at the 20-hour rate.

If a battery can deliver 20 amperes continuously for 20 hours, the battery has a rating of 20 amperes x 20 hours (or 400 ampere-hours). Therefore, the 20-hour rating equals the average current that a battery can supply without interruption for an interval of 20 hours.

4-78. All standard batteries deliver 100 percent of their available capacity if discharged in 20 hours or more. However, they will deliver less than their available capacity if discharged at a faster rate. The faster they discharge, the less ampere-hour capacity they have.

4-79. The low-voltage limit, as specified by the manufacturer, is the limit beyond which very little useful energy can be obtained from a battery. This low-voltage limit is normally a test used in battery shops to determine the condition of a battery.

BATTERY CHARGING

4-80. Adding the active ingredient to the electrolyte of a discharged battery does not recharge the battery. Adding the active ingredient only increases the specific gravity of the electrolyte. It does not convert the plates back to active material; therefore, it does not bring the battery back to a charged condition. A charging current must be passed through the battery to recharge it.

WARNING

A mixture of hydrogen and air can be dangerously explosive. No smoking, electric sparks, or open flames should be permitted near charging.

TYPES OF CHARGES

4-81. Depending on the condition of the battery, the following types of charges may be given to a storage battery:

- Initial charge.
- Normal charge.
- Equalizing charge.
- Floating charge.
- Fast charge.

4-82. **Initial charge**. When a new battery is shipped dry, the plates are in an uncharged condition. Therefore, it is necessary to charge the battery after the electrolyte has been added. Charge the battery using a long, low-rate initial charge. The charge is given according to the manufacturer's instructions. These instructions are shipped with each battery. If, for some reason, the manufacturer's instructions are not available, refer to the detailed instructions for charging batteries found in TM 9-6140-200-14.

4-83. **Normal charge**. A normal charge is a routine charge. This charge is given according to the nameplate data during the ordinary cycle of operation to restore the battery to its charged condition.

4-84. **Equalizing charge**. An equalizing charge is a special extended normal charge that is given periodically to batteries as part of maintenance routine. It ensures that all sulfate is driven from the plates and that all the cells are restored to a maximum specific gravity. The equalizing charge is continued until the specific gravity of all cells, corrected for temperature, shows no change for a four-hour period.

4-85. **Floating charge**. In a floating charge, the charging rate is determined by the battery voltage rather than by a definite current value. The floating charge is used to keep a battery at full charge while the battery is idle or used in light duty. It is sometimes referred to as a trickle charge and is done with low current.

4-86. **Fast charge**. A fast charge is used when a battery must be recharged in the shortest possible time. The charge starts at a much higher rate than is normally used for charging. Since this type of charge may harm the battery, it should be used only in an emergency.

CHARGING RATE

4-87. The charging rate of storage batteries is normally given on the battery nameplate. If the available charging equipment does not have the desired charging rates, use the nearest available rates. However, the rate should never be so high that violent gassing occurs.

CHARGING TIME

4-88. Continue the charge until the battery is fully charged. Take frequent readings of specific gravity during the charge and compare with the reading taken before the battery was placed on charge.

BATTERIES

Questions

1. What is a cell?
2. What makes up a simple cell?
3. What is the purpose of the electrodes?
4. What does the electrolyte provide?
5. What are the two classifications of cells?
6. How can a secondary cell be restored to its original condition?
7. What is electrochemical action?
8. What happens to hydrogen ions in a primary cell when they are positively charged?
9. Can a secondary cell be recharged?
10. What is the name of the action when the flow of current causes hydrogen bubbles to form on the surface of the anode?
11. How can the life of a battery be greatly increased?
12. What is the most popular type of primary cell?
13. Where are the internal parts of a dry cell located?
14. Where should you store unused cells in order to greatly increase their shelf life?
15. What are the four basic types of secondary (wet cells)?
16. What is the most widely used secondary cell?
17. What type of cell is used that requires a high discharge rate?
18. What cell is used extensively to power emergency equipment?
19. What are two disadvantages of the silver-cadmium cell?
20. How can cells be combined?
21. A single cell normally supplies how much voltage?
22. How are cells connected if an electrical load requires only 1.5 volts but will require 1/2 ampere of current?
23. How are the terminals of a lead-acid battery identified?
24. What should be on the outside of secondary cell batteries to tell them apart?
25. What is the name of the battery test that provides a visual and authoritative assessment for cleanliness?
26. At what temperature will a discharged battery freeze?
27. What battery cable should be disconnected first?
28. What does a hydrometer measure?
29. The specific gravity readings (under otherwise specified) should be no greater than how many points?

BATTERIES

Questions

30. Battery connections exposed to the salt air environment are prone to what?
31. A fully charged lead-acid battery has how many volts per cell?
32. What should you do if you splash electrolyte on your skin or into your eyes?
33. How is the capacity of a battery measured?
34. What are the five types of charges for storage battery?

Chapter 5

Concepts of Alternating Current

This TC has already discussed DC (a current that does not change direction). A coil rotating in a magnetic field generates an AC (a current that regularly changes direction). This chapter explains how AC is generated and describes the quantities and terms associated with AC.

ALTERNATING CURRENT AND DIRECT CURRENT

5-1. Alternating current is current that changes constantly in amplitude and which reverses direction at regular intervals. Direct current flows only in one direction. The number of electrons flowing past a point in a circuit in one second determines the amplitude of current. For example, if a coulomb of electrons moves past a point in a wire in one second and all of the electrons are moving in the same direction, the amplitude of DC in the wire is 1 ampere. If one-half coulomb of electrons moves in one direction past a point in the wire in one-half second, then reverses direction and moves past the same point in the opposite direction during the next half-second, a total of 1 coulomb of electrons passes the same point in the wire. The amplitude of the AC is 1 ampere. Figure 5-1 shows this comparison of DC and AC. Notice that one white arrow plus one striped arrow comprises 1 coulomb.

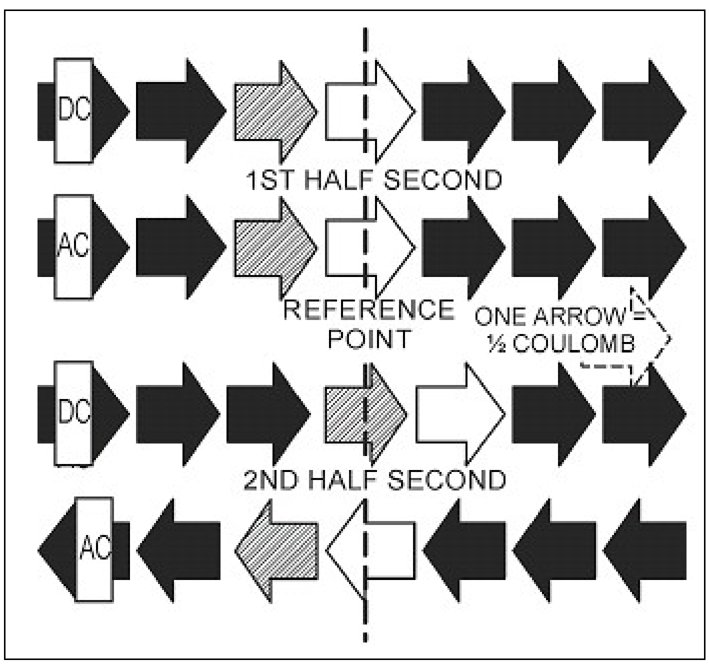

Figure 5-1. Comparing Direct Current and Alternating Current Flow in a Wire

DISADVANTAGES OF DIRECT CURRENT COMPARED TO ALTERNATING CURRENT

5-2. Certain disadvantages in using DC became apparent when commercial use of electricity became widespread in the United States. If a commercial DC system is used, the voltage must be generated at the level (amplitude or value) required by the load. For example, to properly light a 240-volt lamp, the DC generator must deliver 240 volts. If a 120-volt lamp is to be supplied power from a 240-volt generator, a resistor or another 120-volt lamp must be placed in series with the 120-volt lamp to drop the extra 120 volts produced by the generator. When the resistor is used to reduce the voltage, an amount of power equal to that consumed by the lamp is wasted.

5-3. Another disadvantage of the DC system becomes evident when the direct current (I) from the generating station must be transmitted a long distance over wires to the consumer. When this happens, a large amount of power is lost due to the resistance (R) of the wire. The power lost equals I^2R. This loss can be greatly reduced if the power transmitted over the lines is at a very high voltage level and a low current level. However, this is not a practical solution in the DC system because the load would then have to be operated at a dangerously high voltage. Practically all modern commercial electric power companies generate and distribute AC because of the disadvantages related to transmitting and using DC.

5-4. Unlike direct voltages, alternating voltages can be stepped up or down in amplitude by a device called a transformer. Use of the transformer permits efficient transmission of electrical power over long distance lines. At the electrical power station, the transformer output is at high voltage and low current levels. At the consumer end of the transmission lines, the voltage is stepped down by a transformer to the value required by the load. Due to its inherent advantages and versatility, AC has replaced DC in all but a few commercial power and vessel applications.

ELECTROMAGNETISM

5-5. The sine wave is used to illustrate the change in current direction of the AC system. Although there are several ways of producing this current, the method based on the principles of electromagnetic induction is by far the easiest and most common method in use.

5-6. Chapter 2 discussed the fundamental theories concerning simple magnets and magnetism. However, it only briefly mentioned how magnetism can be used to produce electricity. This chapter presents a more in-depth study of magnetism. The main points are how magnetism is affected by an electric current and, conversely, how electricity is affected by magnetism. This general subject area is called electromagnetism. The following relationships between magnetism and electricity must be understood to become proficient in the electrical field:

- An electric current always produces some form of magnetism.
- The most commonly used means for producing or using electricity involves magnetism.
- The peculiar behavior of electricity under certain conditions is caused by magnetic influences.

MAGNETIC FIELDS

5-7. In 1819, Hans Christian Oersted, a Danish physicist, found that a definite relationship exists between magnetism and electricity. He discovered that an electric current is always accompanied by certain magnetic effects and that these effects obey certain laws.

MAGNETIC FIELD AROUND A CURRENT-CARRYING CONDUCTOR

5-8. If a compass is placed near a current-carrying conductor, the compass needle will align itself at right angles to the conductor. This indicates the presence of a magnetic force. The presence of this force can be demonstrated by using the arrangement in Figure 5-2. In views A and B, current flows in a vertical conductor through a horizontal piece of cardboard. The direction of the magnetic field produced by the current can be determined by placing a compass at various points on the cardboard and noting the compass needle deflection. The direction of the magnetic force is assumed to be the direction in which the north pole of the compass points.

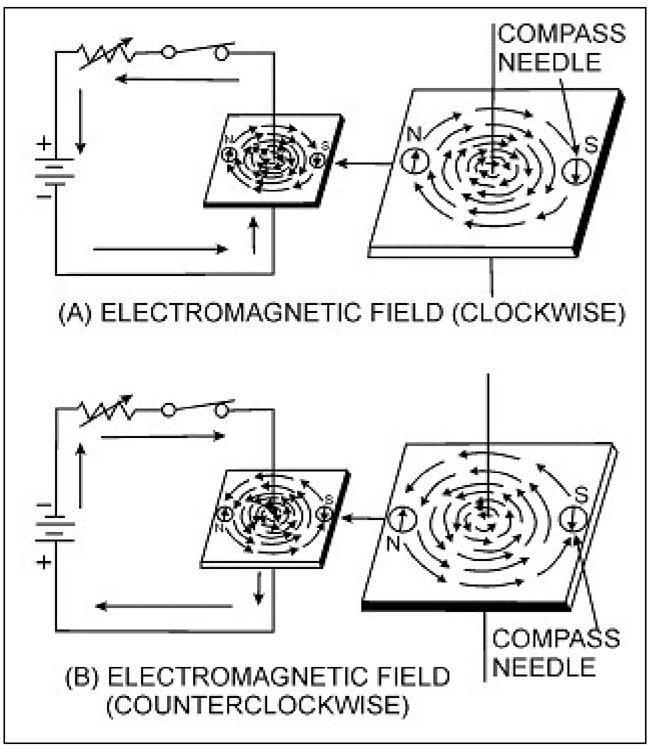

Figure 5-2. Magnetic Field Around a Current-Carrying Conductor

5-9. In Figure 5-2, view A, the needle deflections show that a magnetic field exists in a circular form around a conductor. When the current flows upward (view A), the direction of the field is clockwise as viewed from the top. However, if the polarity of the battery is reversed so that the current flows downward (view B), the direction of the field is counterclockwise.

5-10. The relation between the direction of the magnetic lines of force around a conductor and the direction of the current in the conductor may be determined by means of the left-hand rule for a conductor. If you visualize the conductor in the left hand with your thumb extended in the direction of the electron flow, your finger will point in the direction of the magnetic lines of force. Now apply this rule to Figure 5-2. Note that your fingers point in the direction of the north pole of the compass points when it is placed in the magnetic field surrounding the wire.

5-11. An arrow is generally used in electrical diagrams to denote the direction of current in a length of wire (see Figure 5-3, view A). Where a cross section of wire is shown, an end view of the arrow is used. Figure 5-3, view B, shows a cross-sectional view of a conductor carrying current toward the observer. The direction of current is indicated by a dot, representing the head of an arrow. Figure 5-3, view C, shows a conductor carrying current away from the observer. The direction of current is indicated by a cross, representing the tail of the arrow. The magnetic field around the current-carrying conductor is perpendicular to the conductor and the magnetic lines of force are equal along all parts of the conductor.

5-12. When two adjacent parallel conductors are carrying current in the same direction, the magnetic lines of force combine and increase the strength of the magnetic field around the conductors (see Figure 5-4, view A). Figure 5-4, view B, shows two parallel conductors carrying currents in opposite directions. The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force oppose each other in the space between the wires, thereby deforming the field around each conductor. This means that if two parallel and adjacent conductors are carrying currents in the same direction, the fields about the two conductors aid each other. However, if the two conductors are carrying currents in opposite directions, the fields about the conductors repel each other.

MAGNETIC FIELD OF A COIL

5-13. Figure 5-3, view A, shows that the magnetic field around a current-carrying wire exists at all points along the wire. Figure 5-5 shows that when a straight wire is wound around a core, it forms a coil, and the magnetic field about the core assumes a different shape. Figure 5-5, view A, is actually a partial cutaway view showing the construction of a simple coil. Figure 5-5, view B, shows a cross-sectional view of the same coil. The two ends of the coil are identified as X and Y.

5-14. When current is passed through the coil, the magnetic field about each turn of wire links with the fields of the adjacent turns (see Figure 5-4). The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil is a north pole and the other a south pole.

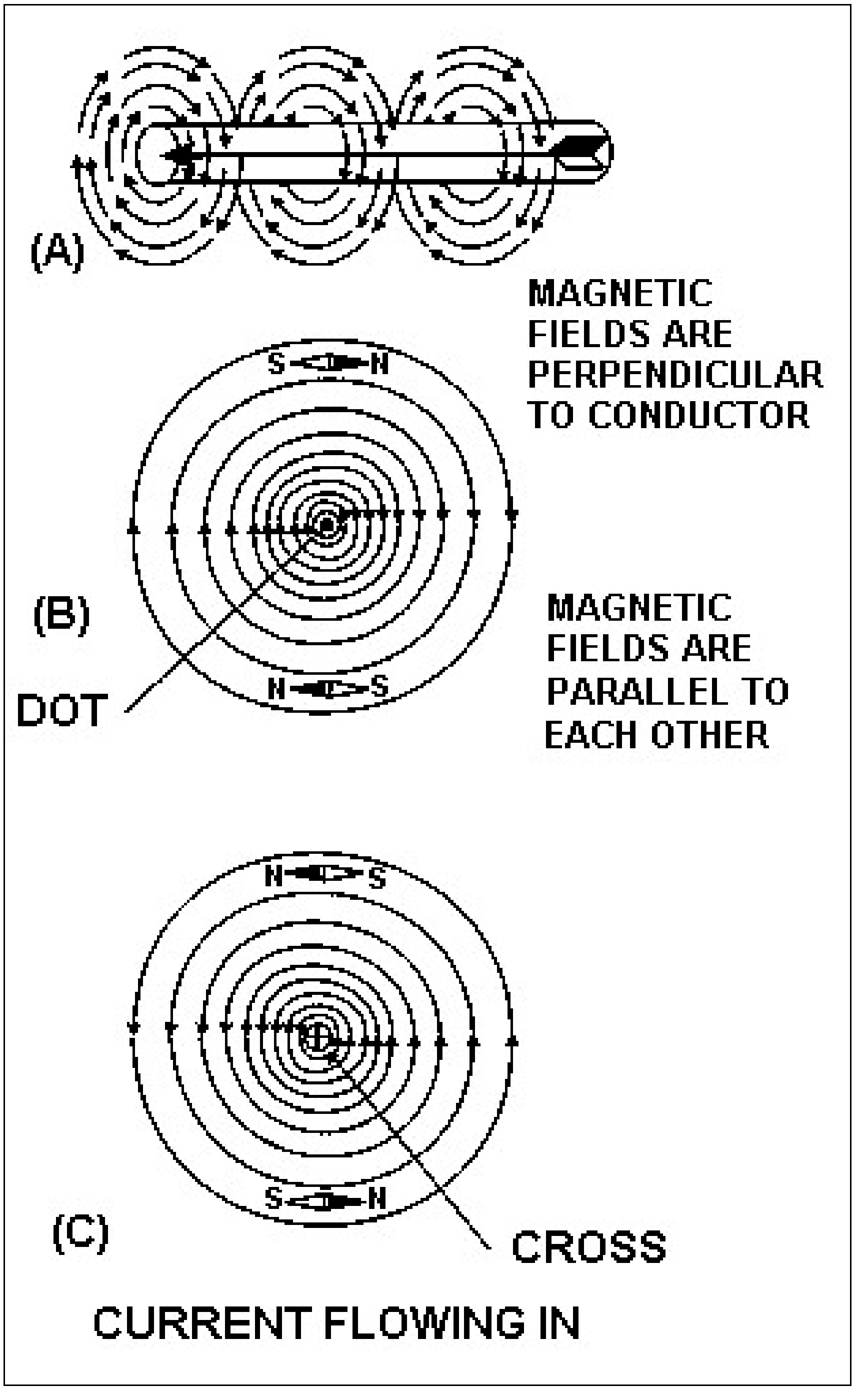

Figure 5-3. Magnetic Field Around a Current-Carrying Conductor, Detailed View

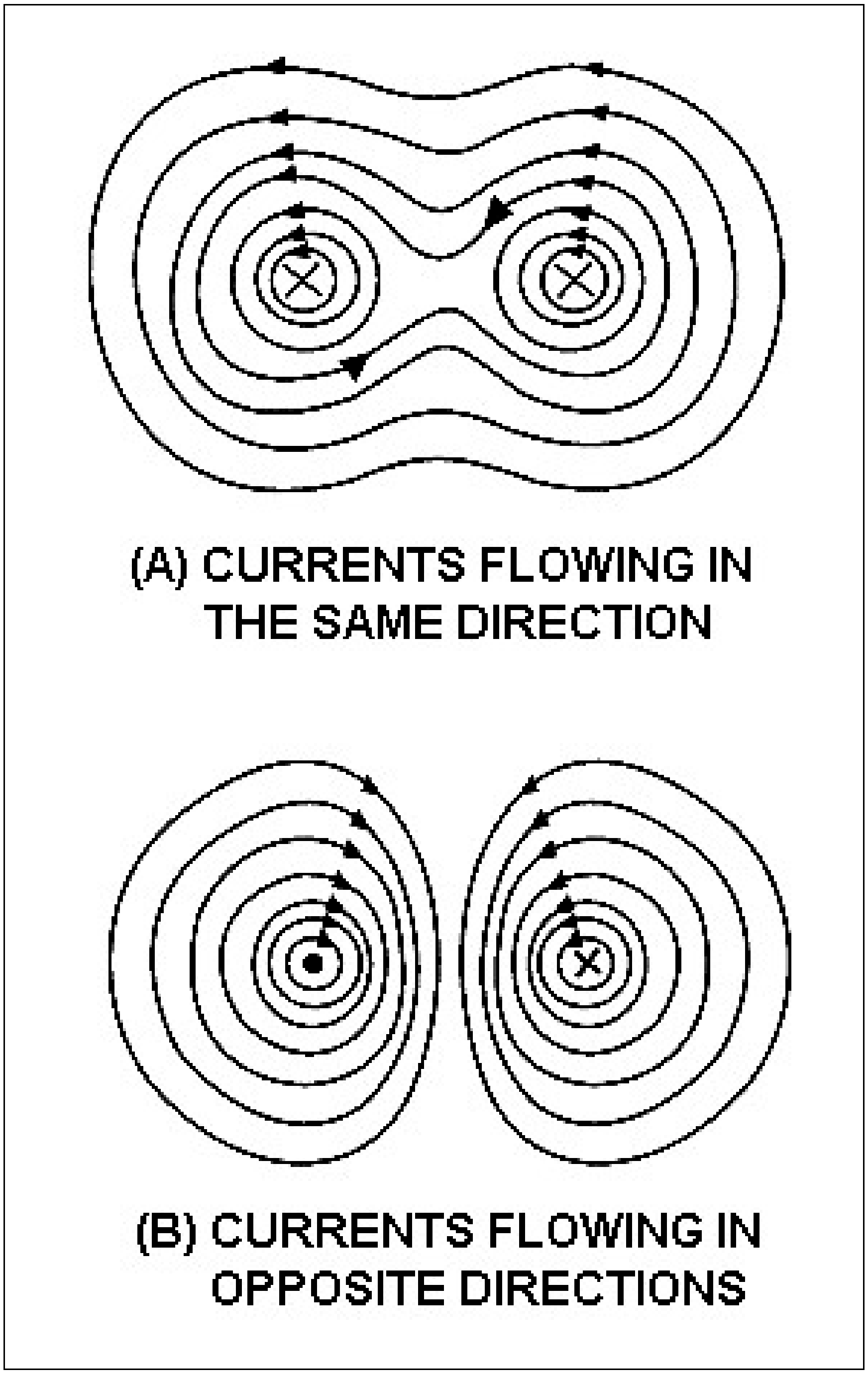

Figure 5-4. Magnetic Field Around Two Parallel Conductors

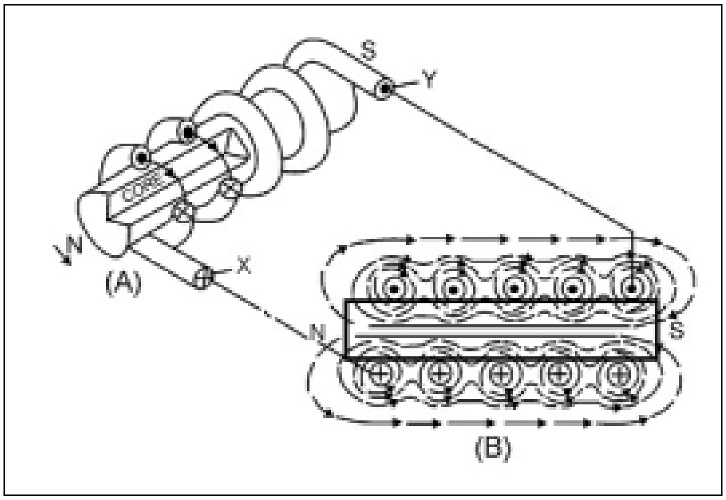

Figure 5-5. Magnetic Field Produced by a Current-Carrying Coil

Polarity of an Electromagnetic Coil

5-15. The direction of the magnetic field around a straight wire depends on the direction of current in that wire. Therefore, a reversal of current in a wire causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current in a coil also causes a reversal of the two-pole magnetic field about the coil.

5-16. When the direction of the current in a coil is known, the magnetic polarity of the coil can be determined by using the left-hand rule for coils. If you visualize grasping the coil in your left hand, with your fingers wrapped around in the direction of the current, your thumb will point toward the north pole of the coil. This rule is illustrated in Figure 5-6.

Strength of a Coil's Electromagnetic Field

5-17. The strength or intensity of a coil's magnetic field depends on a number of factors. The following are the main factors:

- The number of turns of wire in the coil.
- The amount of current flowing in the conductor.
- The ratio of the coil length to the coil width.
- The type of material in the core.

Losses in an Electromagnetic Field

5-18. When current flows in a conductor, the atoms line up in a definite direction, producing a magnetic field. When the direction of current changes, the direction of the atom's alignment also changes, causing the magnetic field to change direction. To reverse all the atoms requires that power be expended and this power is lost. This loss of power (in the form of heat) is called hysteresis loss. Hysteresis loss is common to all AC equipment. However, it causes few problems except in motors, generators, and transformers.

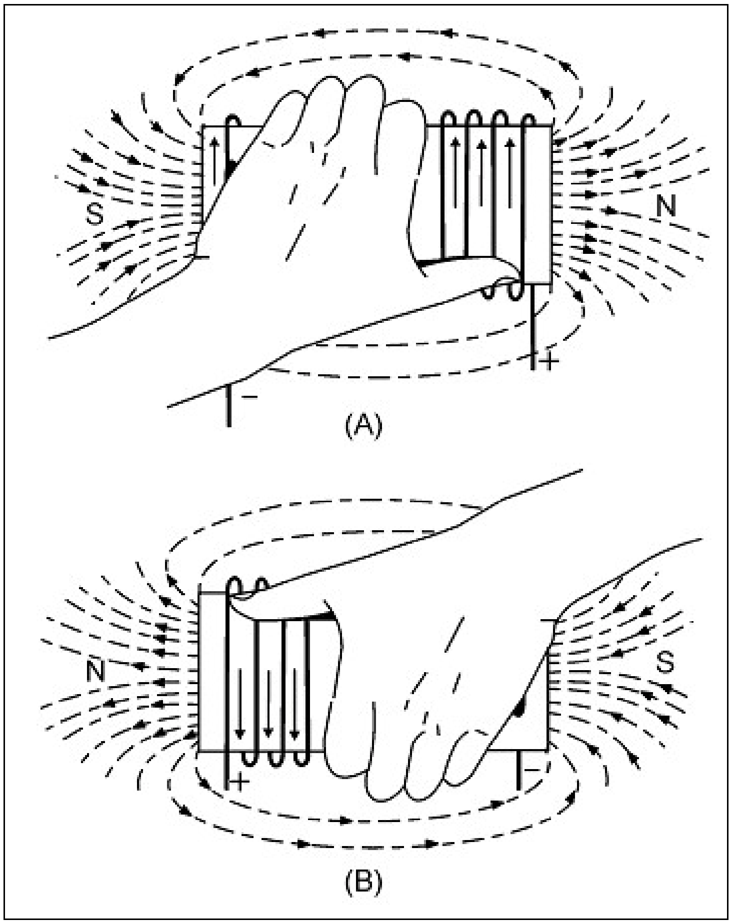

Figure 5-6. Left-Hand Rule for Coils

BASIC ALTERNATING CURRENT GENERATION

5-19. A current-carrying conductor produces a magnetic field around itself. Chapter 2 discussed how a changing magnetic field produces an EMF in a conductor. If a conductor is placed in a magnetic field and either the field or the conductor moves in such a manner that lines of force are interrupted, an EMF is induced in the conductor. This effect is called electromagnetic induction.

CYCLE

5-20. Figure 5-7 shows a suspended loop of wire (conductor) being rotated (moved) in a clockwise direction through the magnetic field between the poles of a permanent magnet. For easy explanation, the loop has been divided into a dark half and a light half. In Figure 5-7, view A, the dark half is moving along (parallel to) the lines of force. As a result, it is cutting no lines of force. The same is true of the light half, which is moving in the opposite direction. No EMF is induced since conductors are cutting no lines of force.

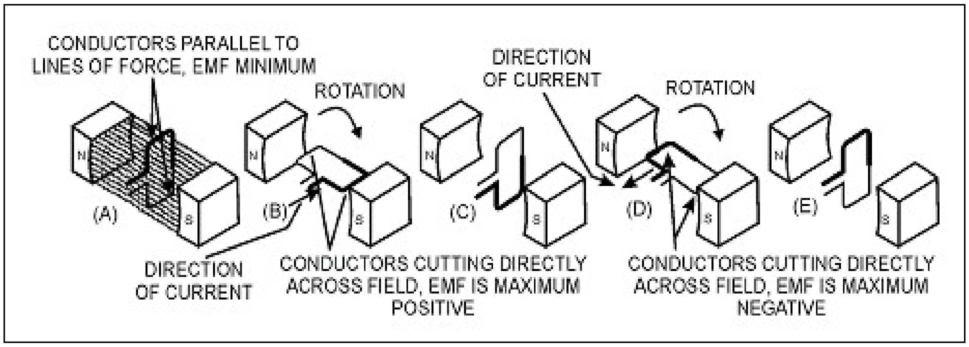

Figure 5-7. Simple Alternating Current Generator

5-21. As the loop rotates toward the position in Figure 5-7, view B, it cuts more and more lines of force per second (inducing an ever-increasing voltage) because it is cutting more directly across the field (lines of force). In view B, the conductor has completed one-quarter of a complete revolution (90 degrees). The voltage induced in the conductor is the maximum since the conductor is now cutting directly across the field. If the induced voltages at various points during the rotation from views A to B are plotted on a graph (and the points connected), the result is the curve shown in Figure 5-8.

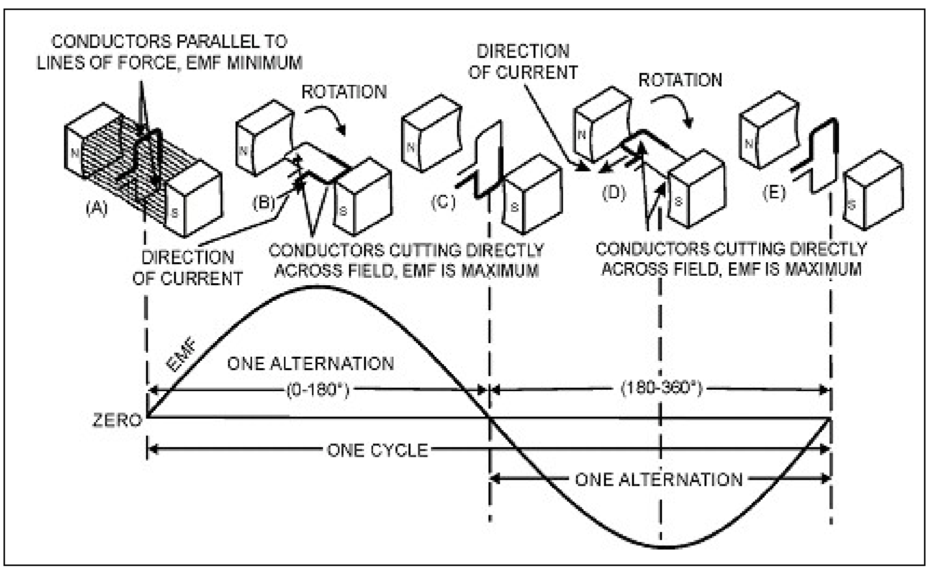

Figure 5-8. Basic Alternating Current Generator

5-22. As the loop continues to be rotated toward the position in Figure 5-7, view C, it cuts fewer and fewer lines of force. The induced voltage will decrease from its peak value. Eventually, the loop is again moving in a plane parallel to the magnetic field and no EMF is induced in the conductor. The loop has now been rotated through half a circle (an alternation or 180 degrees). If the preceding quarter-cycle is plotted, it appears as shown in Figure 5-8.

5-23. When the same procedure is applied to the second half of the rotation (180 degrees through 360 degrees), the curve appears below the horizontal time line. The only difference is in the polarity of the induced voltage. Where previously the polarity was positive, it is now negative.

5-24. The sine curve shows the induced voltage at each instant of time during the rotation of the loop. This curve contains 360 degrees, or two alternations. Two alternations represent one complete cycle of rotation.

5-25. Assuming a closed circuit is provided across the ends of the conductor loop, the direction of current in the loop can be determined by using the left-hand rule for generators (see Figure 5-9). The following describes how to apply the left-hand rule.

5-26. Place your left hand near the illustration with the fingers as shown. Your thumb will point in the direction of rotation (relative movement of the wire to the magnetic field). The forefinger will point in the direction of the magnetic flux (north to south). The middle finger (pointing out of the paper) will point in the direction of current flow.

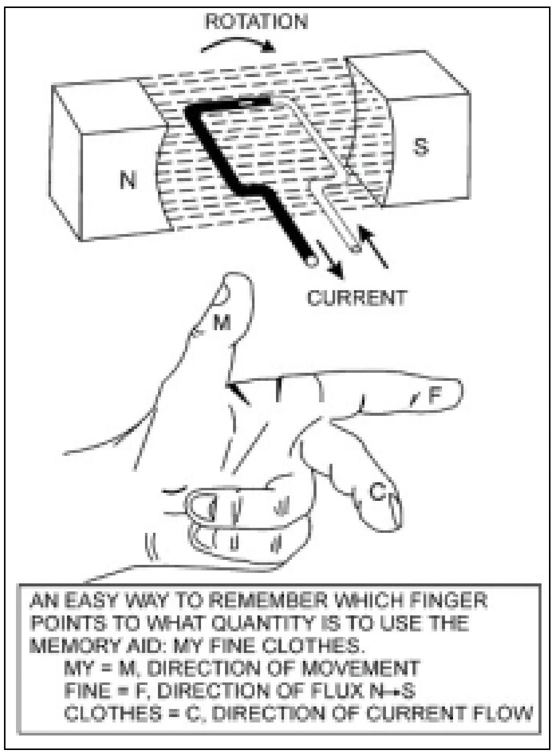

Figure 5-9. Left-Hand Rule for Generators

5-27. When applying the left-hand rule to the dark half of the loop in Figure 5-8, view B, the current flows in the direction indicated by the heavy arrow. Similarly, when applying the left-hand rule on the light half of the loop, the current flows in the opposite direction. The two induced voltages in the loop add together to form one total EMF. This EMF causes the current in the loop.

5-28. When the loop rotates to the position shown in Figure 5-8, view D, the action reverses. The dark half is moving up instead of down and the light half is moving down instead of up. By applying the left-hand rule once again, the total induced EMF and its resulting current have reversed direction. The voltage builds up to maximum in this new direction, as shown by the sine curve. The loop finally returns to its original position (see Figure 5-8, view E). At this point, voltage is again zero. The sine curve represents one complete cycle of voltage generated by the rotating loop. These illustrations show the wire loop moving in a clockwise direction. In actual practice, either the loop or the magnetic field can be moved. Regardless of which is moved, the left-hand rule applies.

5-29. If the loop is rotated through 360 degrees at a steady rate and if the strength of the magnetic field is uniform, the voltage produced is a sine wave of voltage (see Figure 5-8). Continuous rotation of the loop will produce a series of sine-wave voltage cycles or, in other words, AC voltage.

5-30. The cycle consists of two complete alternations in a period of time. The hertz indicates one cycle per second. If one cycle per second is 1 hertz, then 100 cycles per second equal 100 hertz, and so on. This TC uses the term “cycle” when no specific time element is involved and the term “hertz” when the time element is measured in seconds.

FREQUENCY

5-31. If the loop makes one complete revolution each second, the generator produces one complete cycle of AC during each second (1 Hz). Increasing the number of revolutions to two per second produces two cycles of AC per second (2 Hz). The number of complete cycles of AC or voltage completed each second is the frequency. Frequency is always measured and expressed in hertz.

PERIOD

5-32. An individual cycle of any sine wave represents a definite amount of time. Figure 5-10 shows two cycles of a sine wave that has a frequency of 2 hertz. Since two cycles occur each second, one cycle must require one-half second of time. The time required to complete one cycle of a waveform is the period of the wave. In the above example, the period is one-half second. The relationship between time (t) and frequency (f) is indicated by the following formula:

$$t = \frac{1}{f} \quad \text{and} \quad f = \frac{1}{t}$$

Where:

t = period in seconds

f = frequency in hertz

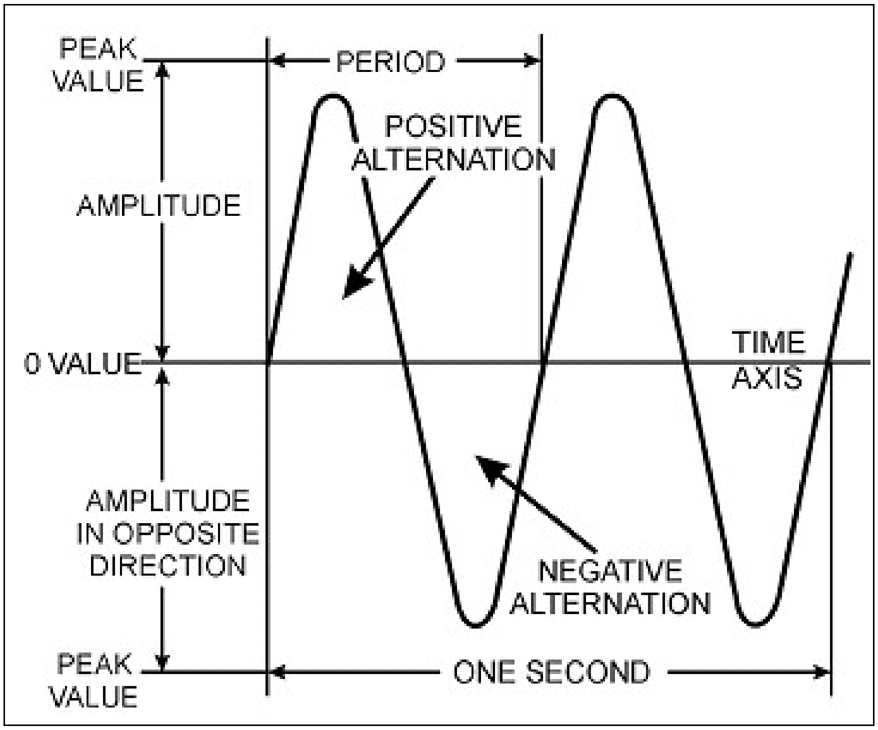

Figure 5-10. Period of a Sine Wave

5-33. Each cycle of the sine wave in Figure 5-10 consists of two identically shaped variations in voltage. The variations that occur during the time considered the positive alternation (above the horizontal line) indicates current movement in one direction. The direction of current movement is determined by the generated terminal voltage polarities. The variations that occur during the time considered the negative alternation (below the horizontal line) indicates current movement in the opposite direction because the generated voltage terminal polarities have reversed.

5-34. The distance from zero to the maximum value of each alternation is the amplitude. The amplitude of the positive alternation and the amplitude of the negative alternation are the same.

WAVELENGTH

5-35. The time it takes for a sine wave to complete one cycle is defined as the period of the waveform. The distance traveled by the sine wave during this period is the wavelength. Wavelength, indicated by the Greek symbol lambda (λ), is the distance along the wave from one point to the same point on the next cycle. Figure 5-11 shows this relationship. The point where waveform measurement of wavelength begins is not important as long as the distance is measured to the same point on the next cycle (see Figure 5-12).

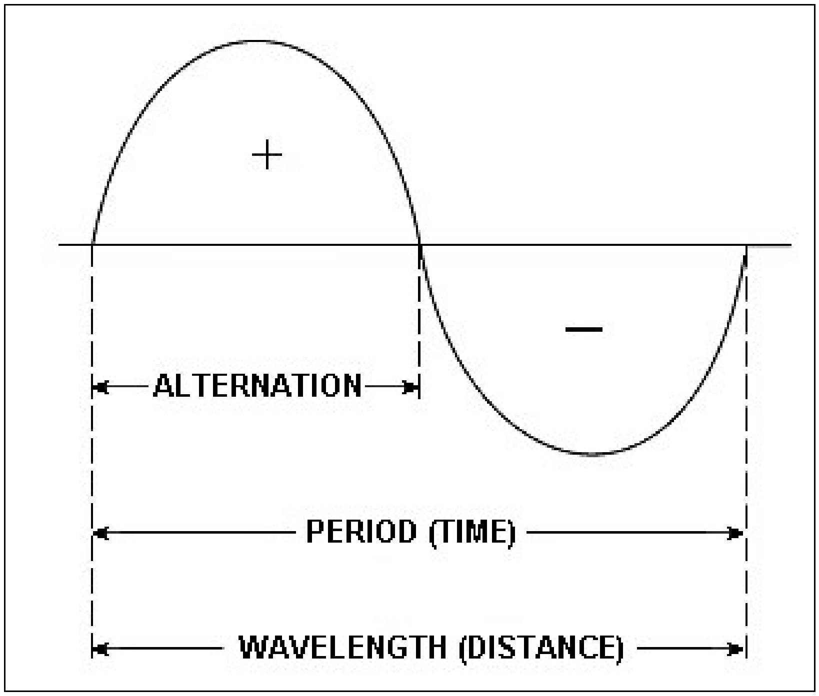

Figure 5-11. Wavelength

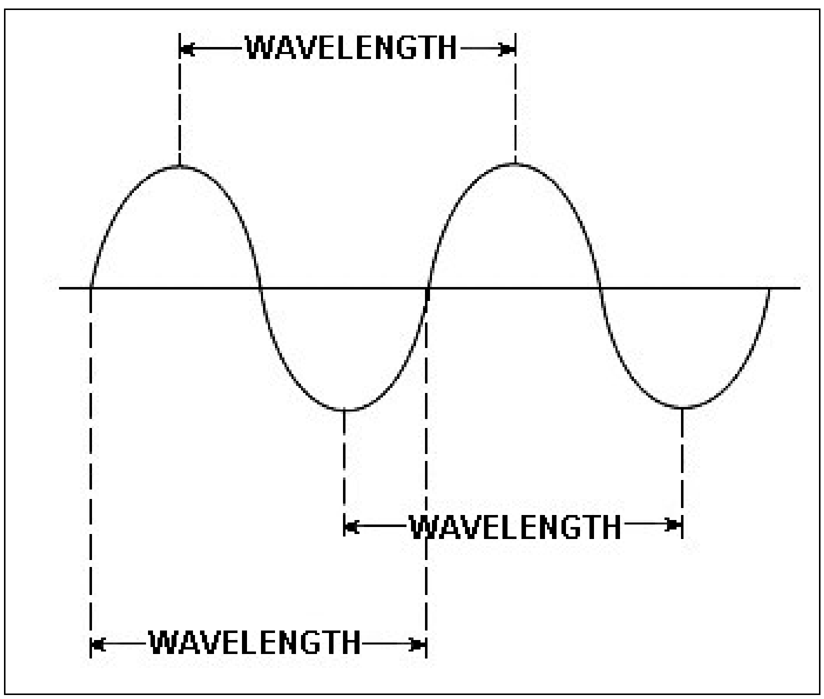

Figure 5-12. Wavelength Measurement

5-36. The sine wave is usually expressed on a scale in degrees. Rather than express the time involved in minute portions of a second, it is more effective to express the single recurring sine wave by how many degrees it takes to complete a wavelength. Remember how the sine wave was developed. The conductor had to rotate 180 degrees to create the positive alternation and 180 degrees more to create the negative alternation (see Figure 5-9). This produced 360 degrees or one complete revolution for a definite period of time. The amount of times this sine wave is repeated every second corresponds to the frequency (cycles per second) and to the speed of the moving conductor (revolutions per minute).

ALTERNATING CURRENT VALUES

5-37. AC and voltage are often expressed in terms of maximum or peak values, peak-to-peak values, effective values, instantaneous values, or average values. Each of these values describes a different amount of the current or voltage.

MAXIMUM OR PEAK VALUE

5-38. Figure 5-13 shows the positive alternation of a sine wave (a half-cycle of AC) and a DC waveform that occur simultaneously. The DC starts and stops at the same moment as the positive alternation and both waveforms rise to the same maximum value. However, the DC values are greater than the corresponding AC values at all points except the point at which the positive alternation passes through its maximum value. At this point, the DC and the AC values are equal. This point on the sine wave is referred to as the maximum or peak value.

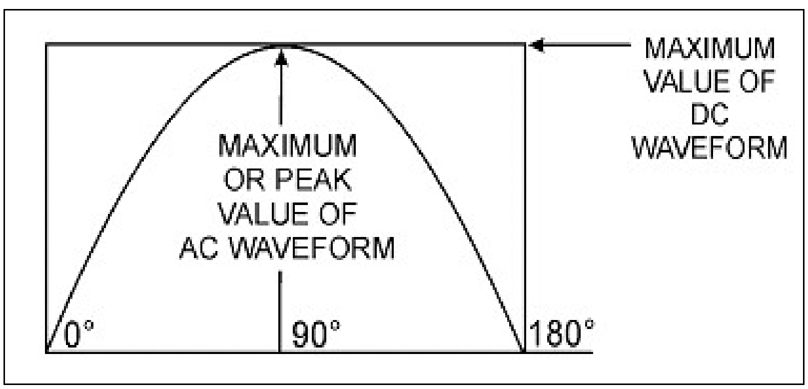

Figure 5-13. Maximum of Peak Value

PEAK-TO-PEAK VALUE

5-39. There are always two maximum or peak values (one for the positive half-cycle and the other for the negative half-cycle) during each complete cycle of AC. The difference between the peak positive value and the peak negative value is the peak-to-peak value of the sine wave. This value is twice the maximum or peak value of the sine wave and is sometimes used to measure AC voltages. Figure 5-14 shows the difference between peak and peak-to-peak values. Alternating voltage and current are usually expressed in effective values rather than in peak-to-peak values.

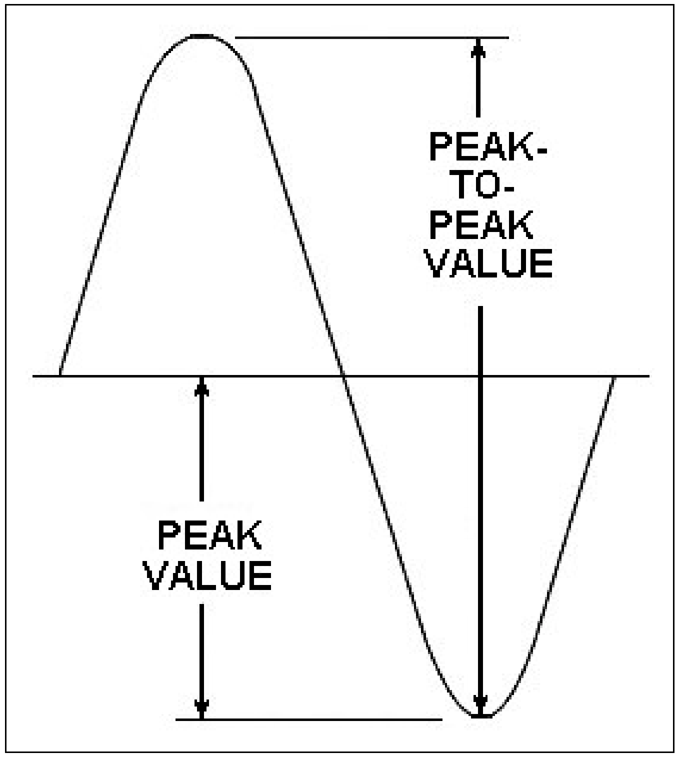

Figure 5-14. Peak and Peak-to-Peak Values

EFFECTIVE VALUE

5-40. The voltage and current values commonly displayed on multimeters and discussed by technicians are called the effective value. Although AC changes in value constantly, a value closely resembling a like value of DC can be expressed. The effective value of AC or voltage has the same effect as a like value of DC. To convert the effective value to a peak value, multiply the effective value by 1.414.

Example:

(450-volt generator effective value) x 1.414 = peak value

(450 volts) x 1.414 = 636.3 volts peak

However, to change the peak value into the effective value, multiply the peak value by .707.

Example:

(636 volt peak value) x .707 = effective value

(636 volts) x .707 = 450 volts effective value

The effective value of AC or voltage is also referred to as root mean square or RMS. The RMS value is derived from the power formula. The RMS value turns out to be 70.7 percent of the peak value. Figure 5-15 shows various values used to indicate sine wave amplitude.

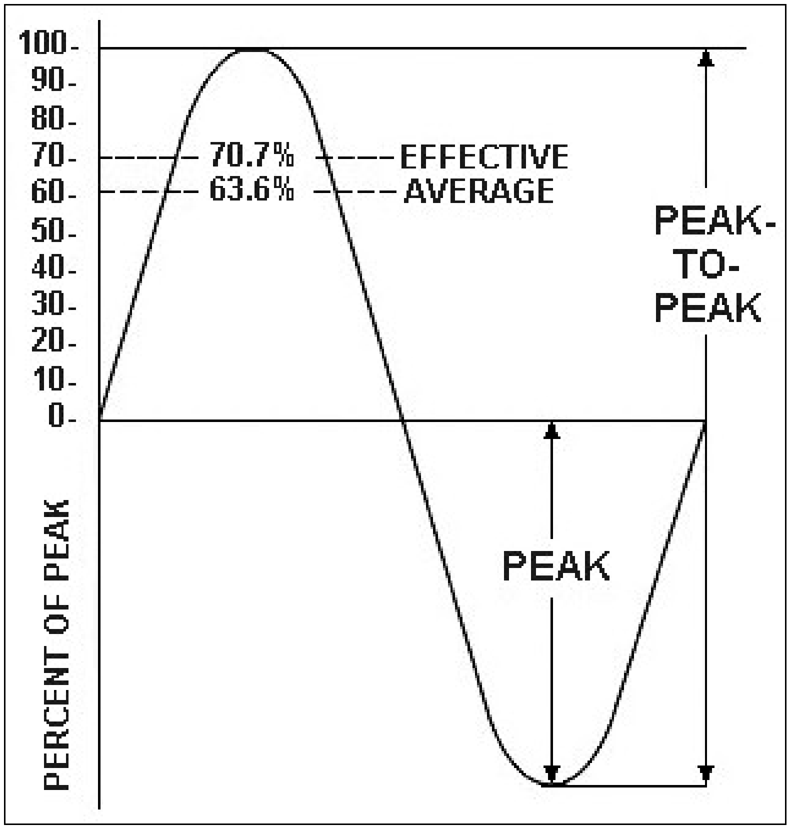

Figure 5-15. Various Values Used to Indicate Sine Wave Amplitude

INSTANTANEOUS VALUE

5-41. The instantaneous value of an alternating voltage or current is the value of voltage or current at one particular instant in time. The value may be zero if the particular instant is the time in the cycle at which the polarity of the voltage is changing. It may also be the same as the peak value, if the selected instant is the time in the cycle at which the voltage or current stops increasing and starts decreasing. There are actually an infinite number of instantaneous values between zero and peak value.

AVERAGE VALUE

5-42. The average value of an AC or voltage is the average of all the instantaneous values during one alternation. Since the voltage increases from zero to peak value and decreases back to zero during one alternation, the average value must be some value between those two limits. The average value can be determined by adding together a series of instantaneous values of the alternation (between 0 and 180 degrees) and then dividing the sum by the number of the instantaneous values used. The computation would show that one alternation of a sine wave has an average value equal to 0.636 times the peak value.

5-43. Do not confuse the above definition of an average value with that of the average value of a complete cycle. Since the voltage is positive during one alternation and negative during the other alternation, the average value of the voltage values occurring during the complete cycle is zero.

SINE WAVES IN PHASE

5-44. When a sine wave of voltage is applied to a resistance, the resulting current is also a sine wave. This follows Ohm's Law which states that current is directly proportional to the applied voltage. In Figure 5-16, the sine wave of voltage and the resulting sine wave of current are superimposed on the same time axis. As the voltage increases in the positive alternation, the current also increases. When two sine waves (such as those in Figure 5-16) are precisely in step with one another, they are in phase. To be in phase, the two sine waves must go through their maximum and minimum points at the same time and in the same direction.

5-45. This action can occur only in a circuit containing a purely resistive load. A resistive load is any device that consumes all power in the form of heat and/or light. Resistors, light bulbs, and some heating elements are examples of these loads. All the power that arrives at the load is consumed at the load. There is no power left over to be returned to the circuit.

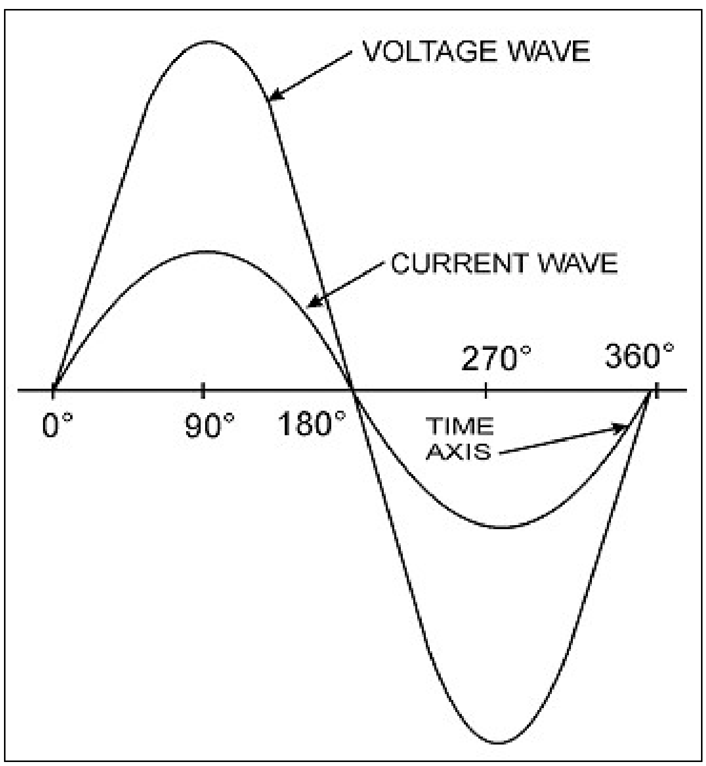

Figure 5-16. Voltage and Current Waves In Phase

SINE WAVES OUT OF PHASE

5-46. Figure 5-17 shows voltage wave E_1 which is considered to start at 0 degrees (time one). As voltage wave E_1 reaches its positive peak, voltage wave E_2 starts its rise (time two). Since these voltage waves do not go through their maximum and minimum points at the same instant in time, a phase difference exists between the two waves. The two waves are out of phase. For the two waves in Figure 5-17, the phase difference is 90 degrees.

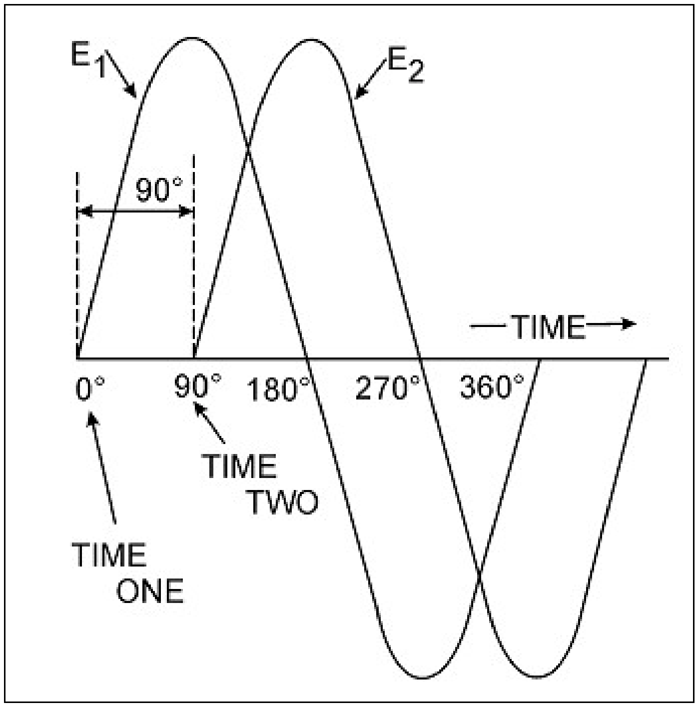

Figure 5-17. Voltage Waves 90 Degrees Out of Phase

5-47. The terms "lead" and "lag" further describe the phase relationship between two sine waves. The amount by which one sine wave leads or lags another sine wave is measured in degrees. In Figure 5-17, wave E_2 starts 90 degrees later in time than does wave E_l. Wave E_1 leads wave E_2 by 90 degrees and wave E_2 lags wave E_1 by 90 degrees.

5-48. One sine wave can lead or lag another sine wave by any number of degrees, except 0 or 360. When the latter condition exists, the two waves are said to be in phase. Therefore, two sine waves that differ in phase by 45 degrees are actually out of phase with each other. Two sine waves that differ in phase by 360 degrees are considered to be in phase with each other.

5-49. Figure 5-18 shows a common phase relationship. The two waves illustrated differ in phase by 180 degrees. Although the waves pass through their maximum and minimum values at the same time, their instantaneous voltages are always of opposite polarity.

5-50. To determine the phase difference between two sine waves, locate the points where the two waves cross the time axis traveling in the same direction. The number of degrees between the crossing points is the phase difference. The wave that crosses the axis at the later time (to the right on the time axis) is said to lag the other wave.

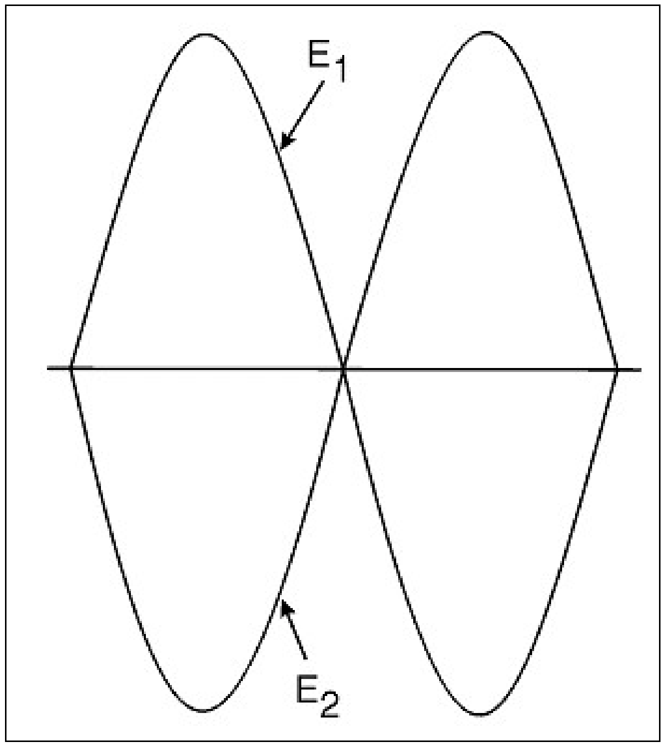

Figure 5-18. Voltage Waves 180 Degrees Out of Phase

OHM'S LAW IN ALTERNATING CURRENT CIRCUITS

5-51. Few circuits contain only resistance. For those circuits that contain purely resistive loads, the same rules apply to these circuits as apply to DC circuits. For purely resistive circuits, Ohm's law can be stated as follows:

$$I_{eff} = \frac{E_{eff}}{R} \quad \text{or} \quad I = \frac{E}{R}$$

5-52. Unless otherwise stated, all AC voltage and current values are given as effective values. Do not mix AC values. When solving for effective values, all values used in the formulas must be effective values. Similarly, when solving for average values, all values must be average values.

5-53. There are many other factors affecting the mathematical values of AC electrical systems. Even with these other outside variables, the engineer can use Ohm's Law to understand the relationship between voltage, current, and resistance.

CONCEPTS OF ALTERNATING CURRENT

Questions

1. What is alternating current?
2. What device is used to step up or step down the amplitude of alternating voltages?
3. What is used to illustrate the change in current direction of the AC system?
4. What does it show when placing a compass near a current-carrying conductor and the needle aligns itself at right angles to the conductor?
5. What is used in electrical diagrams to denote the direction of current in a length of wire?
6. The direction of the magnetic field around a straight wire depends on what?
7. The loss of power (in the form of heat) is known as what?
8. What is it called when lines of force are interrupted and an EMF is induced in the conductor?
9. What rule is used for generators to determine the direction of current in the conductor loop?
10. What does hertz indicate?
11. What is frequency?
12. What is amplitude?
13. What is wavelength?
14. What are the values used to express AC and voltage?
15. From what is the root mean square (RMS) value derived?
16. When are two sine waves in phase?
17. What is a resistive load?
18. All AC voltage and current values (unless otherwise specified) are given as what type of values?

Chapter 6

Inductance

Inductance is the property of a coil that causes energy to be stored in a magnetic field about the coil. The energy is stored so as to oppose any change in current. The study of inductance is a challenging but rewarding segment of electricity. It is challenging because at first it seems that new concepts are being introduced. However, these new concepts are merely extensions of fundamental principles already covered in this TC. The study of inductance is rewarding because a thorough understanding of it will enable you to acquire a working knowledge of electrical circuits more rapidly. This chapter defines inductance and describes the factors that affect it.

CHARACTERISTICS OF INDUCTANCE

6-1. Inductance is the characteristic of an electrical circuit that opposes the starting, stopping, or changing of current flow. The symbol for inductance is L. The basic unit of inductance is the henry (H). One henry equals the inductance required to induce 1 volt in an inductor by a change of current of 1 ampere per second.

6-2. An analogy of inductance is found in pushing a heavy load (such as a wheelbarrow or car). It takes more work to start the load than it does to keep it moving. Once the load starts to move, it is easier to keep the load moving than to stop it again. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a change in velocity. Inductance has the same effect on current in an electrical circuit as inertia has when moving a mechanical object. It requires more energy to start or stop current than it does to keep it flowing.

ELECTROMOTIVE FORCE

6-3. Electromotive force is developed whenever there is relative motion between a magnetic field and a conductor. Electromotive force is a difference of potential or voltage that exists between two points in an electrical circuit. In generators and inductors, the EMF is developed by the action between the magnetic field and the electrons in a conductor. An inductor is a wire that is coiled (such as in a relay coil, motor, or transformer). Figure 6-1 shows EMF generated in an electrical conductor.

6-4. When a magnetic field moves through a stationary conductor, electrons are dislodged from their orbits. The electrons move in a direction determined by the movement of the magnetic lines of flux (see Figure 6-2).

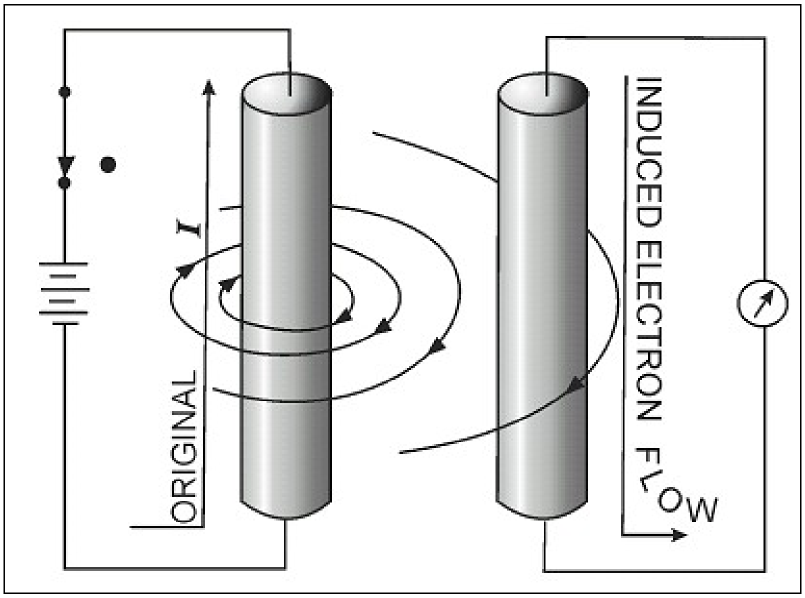

Figure 6-1. Generation of an Electromotive Force in an Electrical Conductor

6-5. The electrons move from one area of the conductor into another area (see Figure 6-2, view A). The area that the electrons moved from has fewer negative charges (electrons) and becomes positively charged (see Figure 6-2, view B). The area the electrons move into becomes negatively charged. The difference between the charges in the conductor equals a difference of potential (or voltage). This voltage, caused by the moving magnetic field, is called electromotive force.

6-6. In simple terms, compare the action of a moving magnetic field on a conductor to the action of a broom. Consider the moving magnetic field to be a moving broom (see Figure 6-2, view C). As the magnetic broom moves along (through) the conductor, it gathers up and pushes before it, loosely bound electrons.

6-7. The area from which electrons are moved becomes positively charged, while the area into which electrons are moved becomes negatively charged. The potential difference between these two areas is the EMF.

SELF-INDUCTANCE

6-8. Even a perfectly straight length of conductor has some inductance. Current in a conductor produces a magnetic field surrounding the conductor. When the current changes direction, the magnetic field changes. This causes relative motion between the magnetic field and the conductor and an EMF is induced in the conductor. This EMF is called a self-induced EMF because it is induced in the conductor carrying the current. It is also called counter electromotive force.

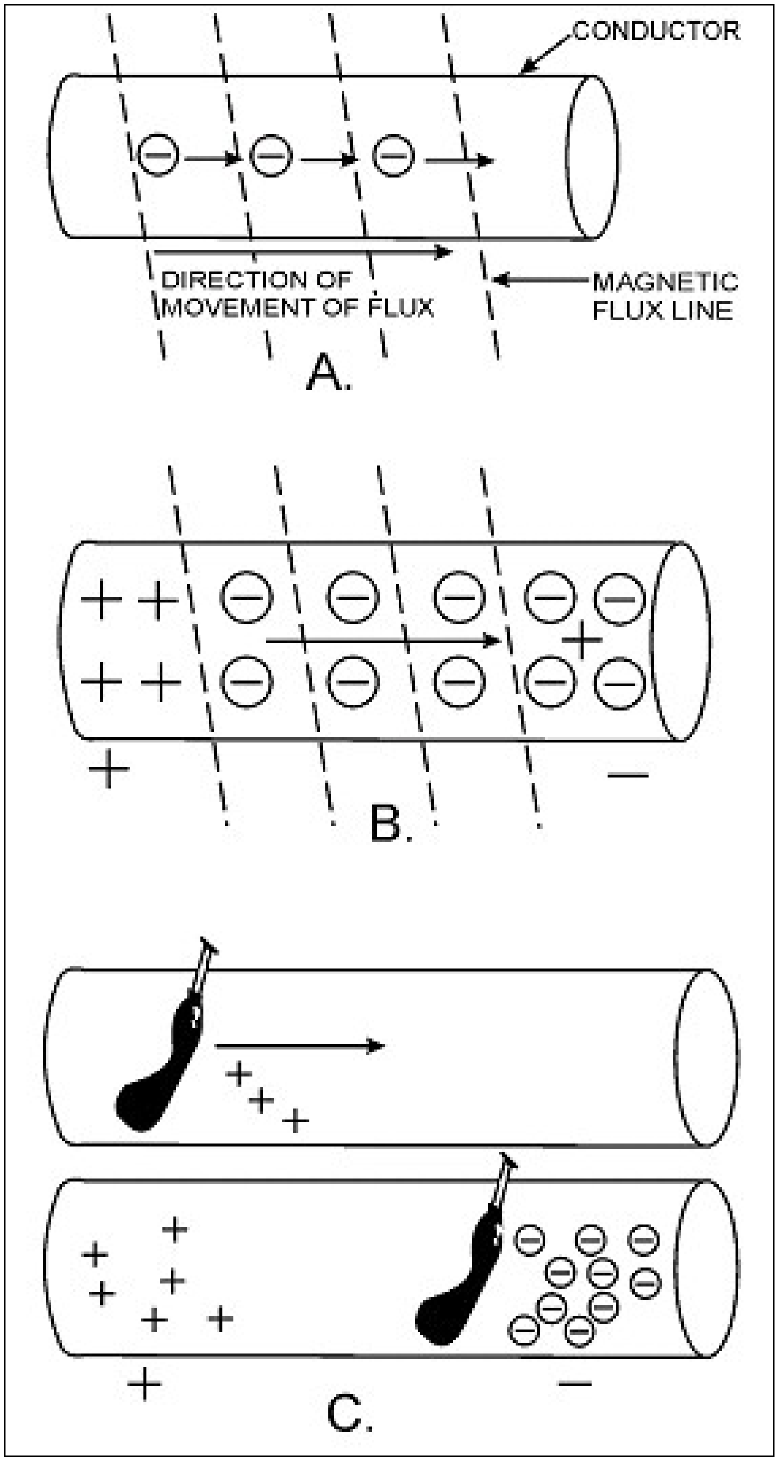

Figure 6-2. Current Movement and Flux Direction Relationship

COUNTER ELECTROMOTIVE FORCE

6-9. To understand what CEMF is and how it develops, first review a basic requirement for the production of voltage. To produce a voltage or EMF magnetically, there must be the following:

- A conductor.
- A magnetic field.
- Relative motion.

Next, review some of the properties of an electrical circuit. DO NOT connect the ends of a length of wire to a terminal of an AC generator. This will cause an electrical short where maximum current would flow. Excessive current would flow because there would be only the minimal resistance of the wire to hold back the current. This will damage the electrical system. Figure 6-3 illustrates self-inductance.

CAUTION

Do not purposefully cause an electrical short. It will damage equipment and may seriously injure personnel.

6-10. If the length of wire is rolled tightly into a coil, the coil would become an inductor. Whenever an inductor is used with AC, a form of power generation occurs. An EMF is created in the inductor because of the close proximity of the coil conductors and the expanding and contracting AC magnetic fields. The inductor creates its own EMF. Since this inductor generator follows the rules of inductance (opposing a change in current), the EMF developed is actually a CEMF opposing the power source creating it. This CEMF pushes back on the electrical system as a form of resistance to the normal power source. CEMF is like having another power source connected in series and opposing.

6-11. This is an example of an inductive load. Unlike the resistive load, all the power in the circuit is not consumed. This effect is summarized in Lenz's law, which states that the induced EMF in any circuit is always in a direction that opposes the effect that produced it.

6-12. The direction of this induced voltage may be determined by applying the left-hand rule for generators. This rule is applied to a portion of conductor 2 that is enlarged for this purpose in Figure 6-3, view A. This rules states that if you point the thumb of your left hand in the direction of relative motion of the conductor and your index finger in the direction of the magnetic field, your middle finger, extended as shown, will indicate the direction of the induced current which will generate the induced voltage (CEMF) as shown.

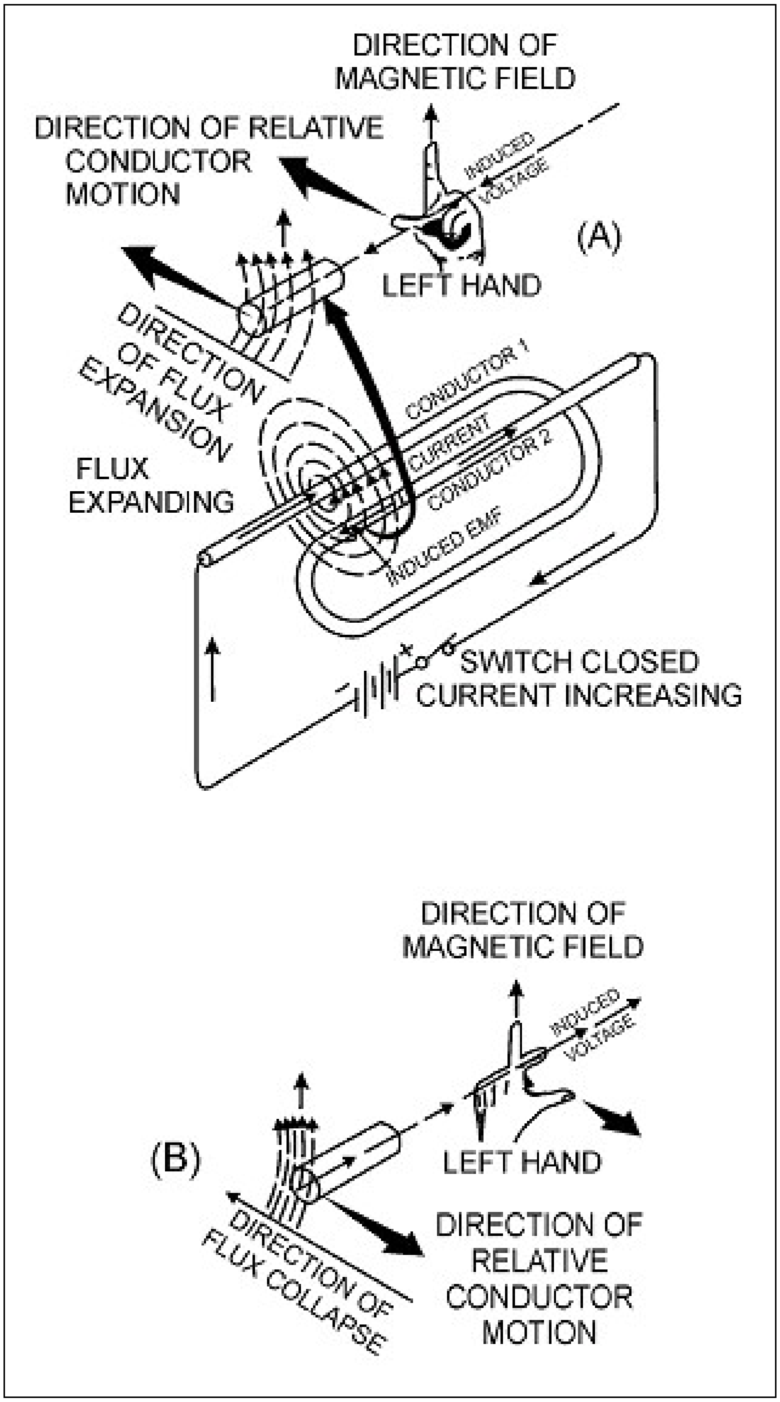

Figure 6-3. Self-Inductance

6-13. Figure 6-3, view B, shows the same section of conductor 2 after the switch has been opened. The flux field is collapsing. Applying the left-hand rule in this case shows that the reversal of flux movement has caused a reversal in the direction of the induced voltage. The induced voltage is now in the same direction as the battery voltage. The self-induced voltage opposes both changes in current. That is, when the switch is closed, this voltage delays the initial buildup of current by opposing the battery voltage. When the switch is opened, it keeps the current flowing in the same direction by aiding the battery voltage.

6-14. Therefore, when a current is building up, it produces a growing magnetic field. This field induces an EMF in the direction opposite to the actual flow of current. This induced EMF opposes the growth of the current and the growth of the magnetic field. If the increasing current had not set up a magnetic field, there would have been no opposition to its growth. The whole reaction, or opposition, is caused by the creation or collapse of the magnetic field, the lines of which (as they expand or contract) cut across the conductor and develop the CEMF (see Figure 6-4).

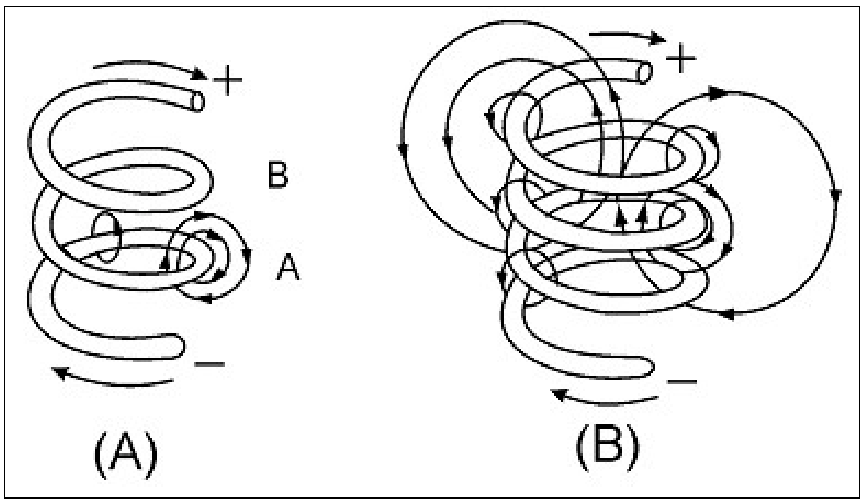

Figure 6-4. Inductance

6-15. Inductors are classified according to core type. The core is the center of the inductor just as the core of an apple is the center of the apple. Forming a coil of wire around a core will make the inductor. The core material is normally one of two types: soft iron or air. Figure 6-5, view A, shows an iron core inductor and its schematic symbol (represented with lines across the top of the inductor to indicate the presence of an iron core). The air core inductor may be nothing more than a coil of wire. It is usually a coil formed around a hollow form of some nonmagnetic material such as cardboard. This material serves no purpose other than to hold the shape of the coil. Figure 6-5, view B, shows an air core inductor and its schematic symbol.

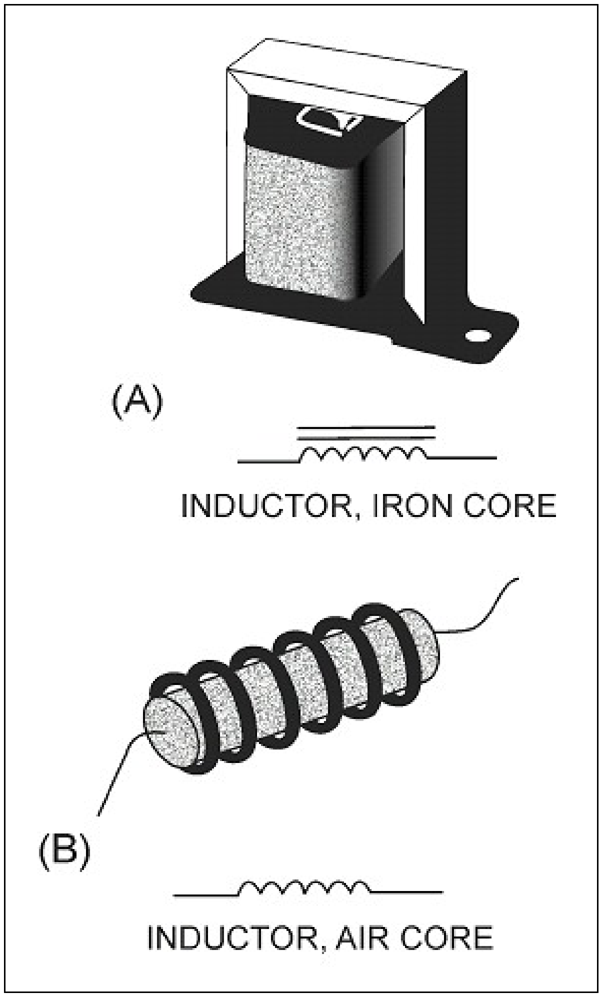

Figure 6-5. Inductor Types and Schematic Symbols

FACTORS AFFECTING COIL INDUCTANCE

6-16. Several physical factors affect the inductance of a coil. They include:

- The number of turns.
- The coil diameter.
- The length of the coil conductor.
- The type of core material.
- The number of layers of winding in the coil.

Inductance depends entirely on the physical construction of the circuit. It can be measured only with special laboratory instruments.

6-17. **Number of turns**. The first factor that affects the inductance of the coil is the number of turns. Figure 6-6, view A, shows a coil with two turns and view B shows a coil with four turns. In coil A, the flux field set up by one loop cuts one other loop. In coil B, the flux field set up by one loop cuts three other loops. Doubling the number of turns in the coil produces a field twice as strong if the same current is used. A field twice as strong, cutting twice the number of turns, will induce four times the voltage. Therefore, inductance varies by the square of the number of turns.

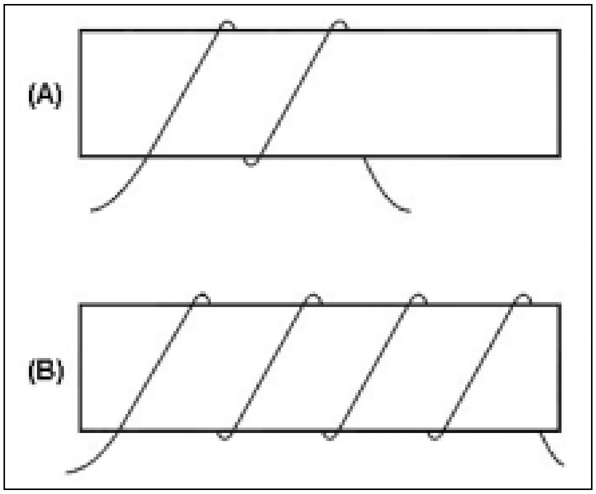

Figure 6-6. Inductor Factor (Turns)

6-18. **Coil diameter**. The second factor is the coil diameter. In Figure 6-7, coil B has twice the diameter of coil A. Physically, it requires more wire to construct a coil of larger diameter than one of smaller diameter with an equal number of turns. Therefore, more lines of force exist to induce a CEMF in the coil with the larger diameter. Actually, the inductance of a coil increases directly as the cross-sectional area of the core increases. Remember that the formula for the area of a circle is $A = \pi r^2$. Doubling the radius of a coil increases the area by a factor of four.

6-19. **Coil length**. The third factor that affects the inductance of a coil is the length of the coil. Figure 6-8 shows two examples of coil spacing. Coil A has three turns, rather widely spaced, making a relatively long coil. A coil of this type has fewer flux linkages due to the greater distance between each turn. Therefore, coil A has a relatively low inductance. Coil B has closely spaced turns, making a relatively short coil. This close spacing increases the flux linkage, increasing the inductance of the coil. Doubling the length of a coil while keeping the number of turns of a coil the same, halves the inductance.

6-20. **Core material**. The fourth factor is the type of core material used with the coil. Figure 6-9 shows an air core (view A) and a soft-iron core (view B). The magnetic core of coil B is a better path for magnetic lines of force than the nonmagnetic core of coil A. The soft-iron magnetic core's high permeability has less reluctance to the magnetic flux. This results in more magnetic lines of force. This increase in the magnetic lines of force increases the number of lines of force cutting each loop of the coil. This increases the inductance of the coil. The inductance of a coil increases directly as the permeability of the core material increases.

6-21. **Coil Windings**. The fifth factor is the number of layers of windings in the coil. Inductance is increased by winding the coil in layers. Figure 6-10 shows three cores with different amounts of layering. Coil A is a poor inductor compared to the others because its turns are widely spaced with no layering. The flux movement, indicated by the dashed arrows, does not link effectively because there is only one layer of turns. Coil B is a more inductive coil. The turns are closely spaced and the wire has been wound in two layers. The two layers link each other with greater number of flux loops during all flux movements. Note that nearly all the turns (such as X) are next to four other turns (shaded). This causes the flux linkage to be increased.

6-22. A coil can be still be made more inductive by winding it in three layers (see Figure 6-10, coil C). The increased number of layers (cross-sectional area) improves flux linkage even more. Some turns (such as Y) lie directly next to six other turns (shaded). In actual practice, layering can continue on through many more layers. The inductance of a coil increases with each layer added.

6-23. The factors that affect the inductance of a coil vary. Differently constructed coils can have the same inductance. Inductance depends on the degree of linkage between the wire conductors and the electromagnetic field. In a straight length of conductor, there is very little flux linkage between one part of the conductor and another. Therefore, its inductance is extremely small. Conductors are much more inductive when they are wound into coils. This is true because there is maximum flux linkage between the conductor turns, which lie side by side in the coil.

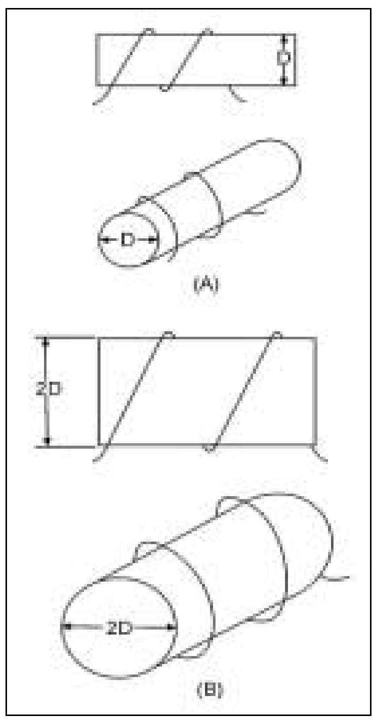

Figure 6-7. Inductance Factor (Diameter)

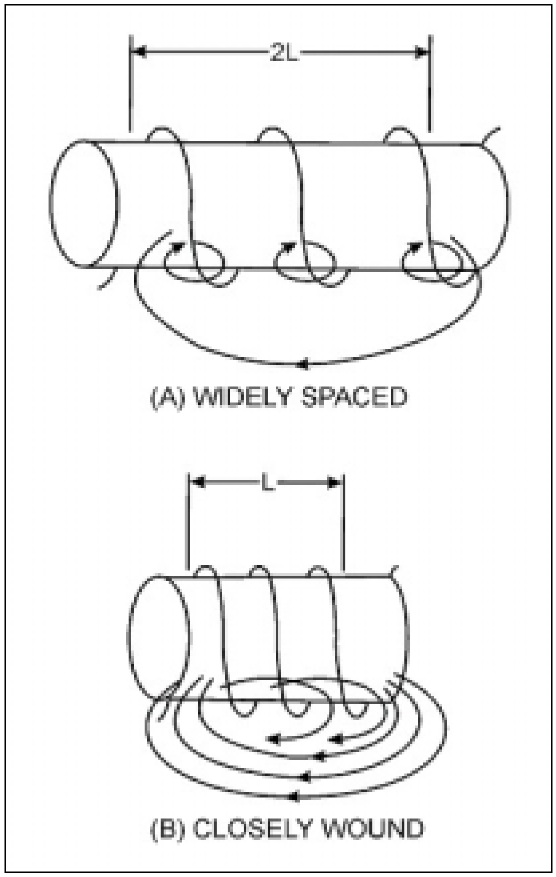

Figure 6-8. Inductance Factor (Coil Length)

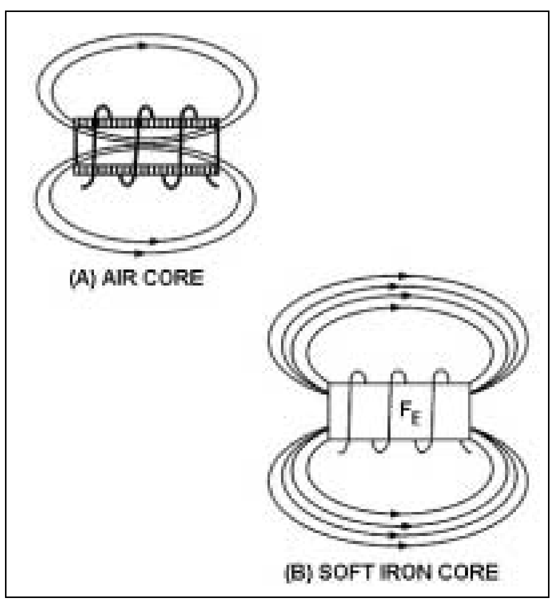

Figure 6-9. Inductance Factor (Core Materials)

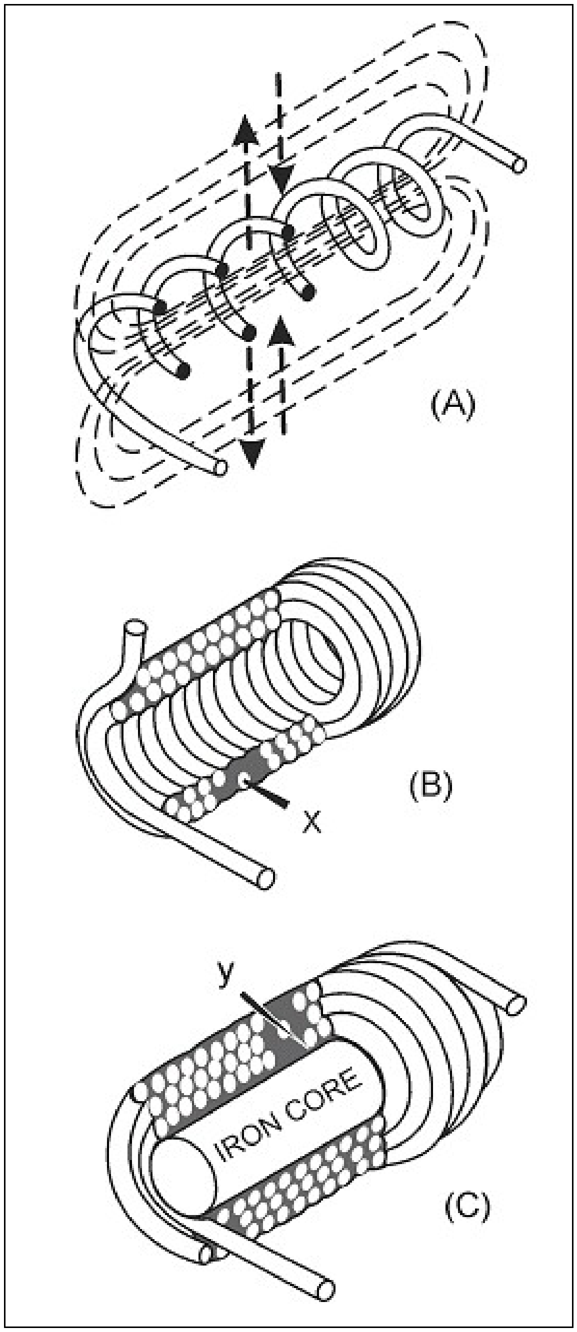

Figure 6-10. Coils of Various Inductances

UNIT OF INDUCTANCE

6-24. As already stated, the basic unit of inductance is the henry. An inductor has an inductance of 1 henry if an EMF of 1 volt is inducted in the inductor when the current through the inductor is changing at the rate of 1 ampere per second.

POWER LOSS IN AN INDUCTOR

6-25. Since an inductor (coil) consists of a number of turns of wire and because all wire has some resistance, every inductor has a certain amount of resistance. This resistance is normally small. It is usually neglected in solving various types of AC circuit problems because the reactance of the inductor (the opposition to AC) is so much greater than the resistance, that the resistance has a negligible effect on current.

6-26. Since some inductors are designed to carry relatively large amounts of current, considerable power can be dissipated in the inductor even though the amount of resistance in the inductor is small. This wasted power is called copper loss. The copper loss of an inductor can be calculated by multiplying the square of current in the inductor by the resistance of the winding (I^2R).

6-27. In addition to copper loss, an iron-core coil (inductor) has two types of iron losses. These are hysteresis loss and eddy-current loss. Hysteresis loss is due to power that is consumed in reversing the magnetic field of the inductor core each time the direction of current in the inductor changes. Eddy-current loss is due to currents that are induced in the iron core by the magnetic field around the turns of the coil. These currents are called eddy currents and flow back and forth in the iron core.

6-28. All these losses dissipate power in the form of heat. Since this power cannot be productively consumed in the electrical circuit, it is lost power.

MUTUAL INDUCTANCE

6-29. Whenever two coils are located so that the flux from one coil links with the turns of another coil, a change of flux in one causes an EMF to be induced into the other coil. This allows the energy from one coil to be transferred or coupled to the other coil. The two coils are coupled or linked by the property of mutual inductance. The symbol for mutual inductance is M. The amount of mutual inductance depends on the relative positions of the two coils. As illustrated in Figure 6-11, if the coils are separated a considerable distance, the amount of flux common to both coils is small and the mutual inductance is low. However, if the coils are close together so that nearly all the flux of one coil links the turns of the other, the mutual inductance is high.

6-30. The mutual inductance can be greatly increased by mounting the coils on a common core. Figure 6-12 illustrates two coils that are placed close together. Coil 1 is connected to a battery through switch S and coil 2 is connected to an ammeter (A). When switch S is closed (view A), the current that flows in coil 1 sets up a magnetic field that links with coil 2. This will cause an induced voltage in coil 2 and a momentary deflection of the ammeter. When the current in coil 1 reaches a steady value, the ammeter returns to zero. If switch S is now opened (view B), the ammeter (A) deflects momentarily in the opposite direction, indicating a momentary flow of current in the opposite direction of coil 2. This current in coil 2 is produced by the collapsing magnetic field of coil 1.

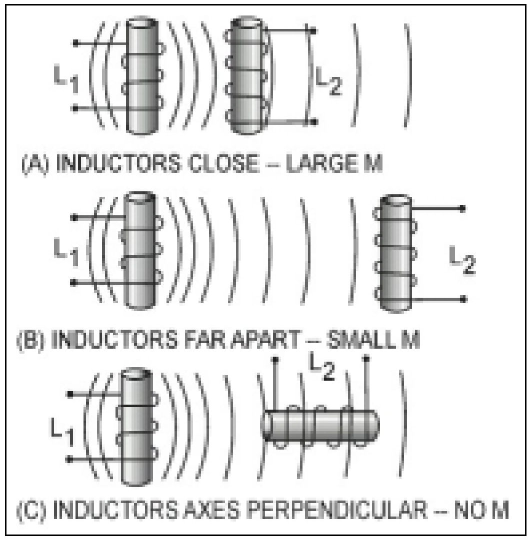

Figure 6-11. Effect of the Position of Coils on Mutual Induction

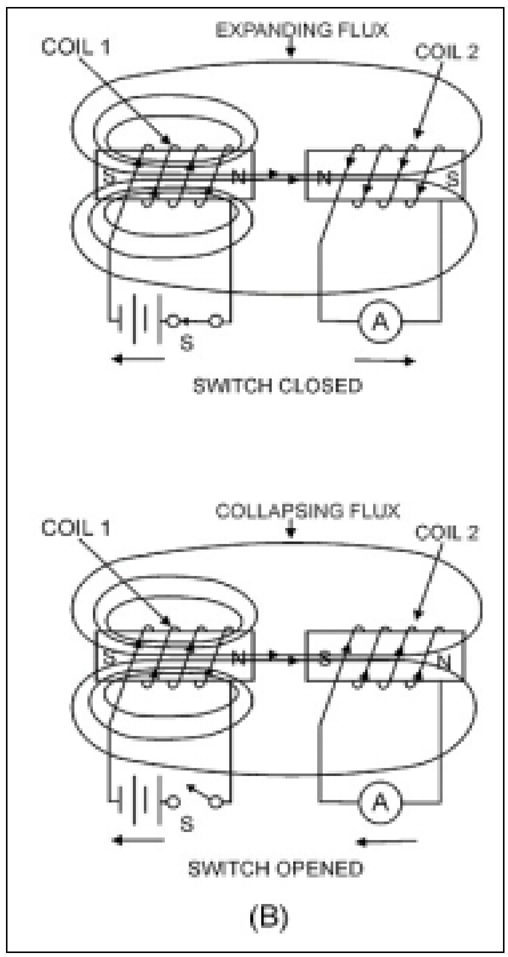

Figure 6-12. Mutual Inductance

INDUCTANCE

Questions

1. What is inductance?
2. What is the basic unit of inductance?
3. What is inertia?
4. When is electromotive force developed?
5. What happens when electrons enter into an area?
6. What is another name for self-induced EMF?
7. What is needed to produce a voltage or EMF magnetically?
8. What does Lenz's law state?
9. How are inductors classified?
10. What are the physical factors that affect the inductance of a coil?
11. What happens to the inductance of a coil with each new layer added?
12. When are conductors more inductive?
13. How do you calculate the copper loss of an inductor?
14. How can mutual inductance be greatly increased?

Chapter 7

Capacitance

Capacitance, like inductance, causes a storage of energy. A capacitor is a device that stores energy in an electrostatic field. The energy is stored so as to oppose any change in voltage. This chapter explains the principles of an electrostatic field as it is applied to capacitance and how capacitance opposes a change in voltage.

ELECTROSTATIC FIELD

7-1. Opposite electrical charges attract each other while like electrical charges repel each other. The reason for this is the existence of an electrostatic field. Any charged particle is surrounded by invisible lines of force called electrostatic lines of force. The following are some interesting characteristics for lines of force:

- They are polarized from positive to negative.
- They radiate from a charged particle in straight lines and do not form closed loops.
- They have the ability to pass through any known material.
- They have the ability to distort the orbits of tightly bound electrons.
- An electrostatic charge can exist only in an insulator.

7-2. Figure 7-1 represents two unlike charges surrounded by their electrostatic field. Since an electrostatic field is polarized positive to negative, arrows are shown radiating away from the positive charge and toward the negative charge. Stated another way, the field from the positive charge is pushing while the field from the negative charge is pulling. The effect of the field is to push and pull the unlike charges together.

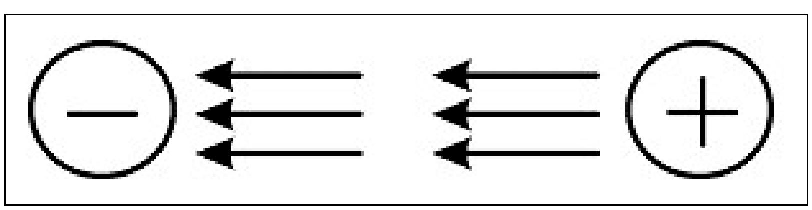

Figure 7-1. Electrostatic Lines of Force Surrounding Two Unlike Charged Particles

7-3. Figure 7-2 shows two like charges with their surrounding electrostatic field. The effect of the electrostatic field is to push the charges apart.

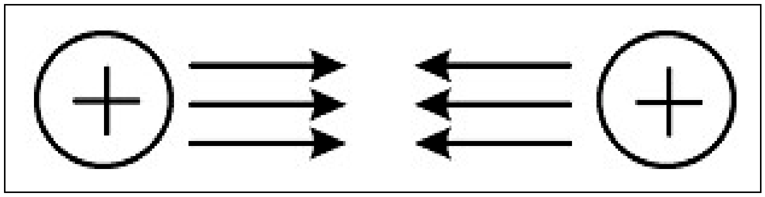

Figure 7-2. Electrostatic Lines of Force Surrounding Two Like Charged Particles

7-4. If two unlike charges are placed on opposite sides of an atom whose outermost electrons cannot escape their orbits, the orbits of the electrons are distorted. Figure 7-3, view A, shows the normal orbit. Figure 7-3, view B, shows the same orbit in the presence of charged particles. Since the electron is a negative charge, the positive charge attracts the electrons, pulling the electrons closer to the positive charge. The negative charge repels the electrons, pushing them further from the negative charge. It is this ability of an electrostatic field to attract and to repel charges that allows the capacitor to store energy.

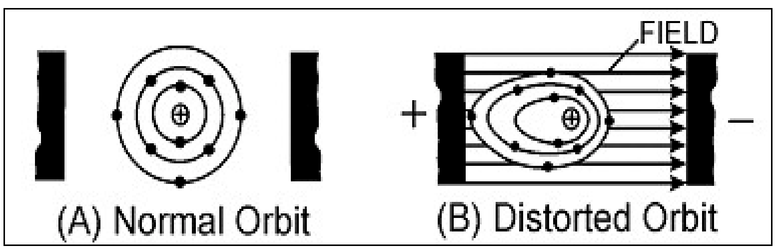

Figure 7-3. Distortion of an Electron's Orbit Due to Electrostatic Force

SIMPLE CAPACITOR

7-5. A simple capacitor consists of two metal plates separated by an insulating material called a dielectric (see Figure 7-4). One plate is connected to the positive terminal of a battery. The other plate is connected to the negative terminal of the battery. An insulator is a material whose electrons cannot easily escape their orbits. Due to the battery voltage, plate A is charged positively and plate B is charged negatively. Therefore, an electrostatic field is set up between the positive and negative plates. The electrons on the negative plate (plate B) are attracted to the positive charges on the positive plate (plate A).

7-6. The orbits of the electrons are distorted in the electrostatic field. This distortion occurs because the electrons in the dielectric are attracted to the top plate while being repelled from the bottom plate. When switch S1 is opened, the battery is removed from the circuit and the charge is retained by the capacitor. This occurs because the dielectric material is an insulator and electrons in the bottom plate (negative charge) have no path to reach the top plate (positive charge). The distorted orbits of the atoms of the dielectric plus the electrostatic force of attraction between the two plates hold the positive and negative charges in their original position. Therefore, the energy that came from the battery is now stored in the electrostatic field of the capacitor.

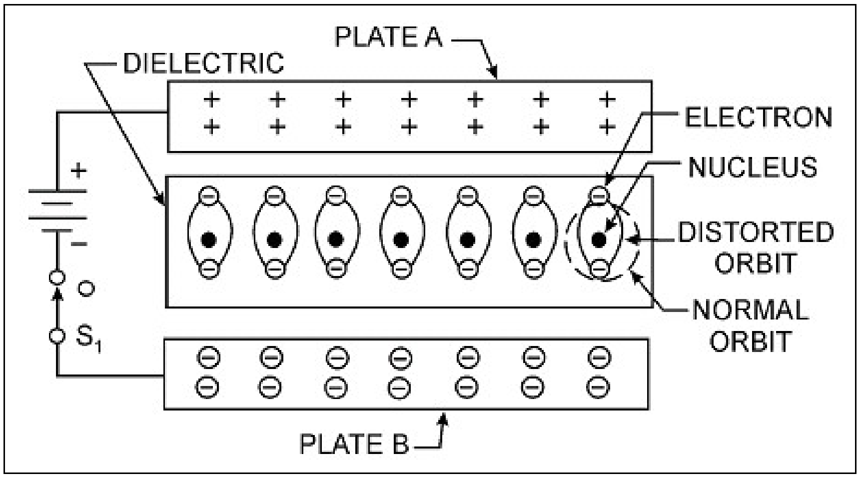

Figure 7-4. Distortion of Electron Orbits in a Dielectric

7-7. Figure 7-5 shows two different symbols for a capacitor. In view (A) the symbol is composed of two plates separated by a space that represents the dielectric. In view (B) the curved plate of the symbol represents the plate that should be connected to a negative polarity.

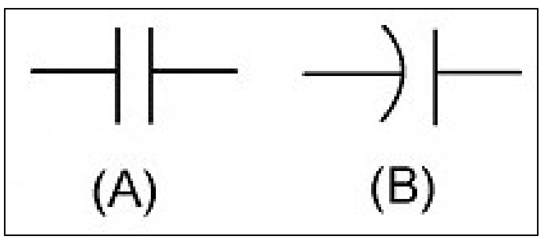

Figure 7-5. Circuit Symbols for Capacitors

THE FARAD

7-8. Capacitance is measured in units called farads. A 1-farad capacitor stores 1 coulomb (a unit of charge [Q] equal to 6.242 x 10^{18} electrons) of charge when a potential of 1 volt is applied across the terminals of a capacitor. This can be expressed by the formula:

$$\text{C (farads)} = \frac{\text{Q (coulombs)}}{\text{E (volts)}}$$

7-9. The farad is a very large unit of measurement of capacitance. For convenience, the microfarad or the picofarad is used. Capacitance is a physical property of the capacitor. It does not depend on circuit characteristics of voltage, current, and resistance. A given capacitor always has the same value of capacitance (farads) in one circuit as in any other circuit in which it is installed.

FACTORS AFFECTING THE VALUE OF CAPACITANCE

7-10. The value of capacitance of a capacitor depends upon three factors:

- The area of the plates.
- The distance between the plates.
- The dielectric constant of the insulating material between the plates.

7-11. Plate area affects the value of capacitance in the same way that size of a container affects the amount of liquid that can be held by the container. A capacitor with a large plate area can store more charges than a capacitor with a small plate area. Simply stated, the larger the plate area, the larger the capacitance.

7-12. The second factor affecting capacitance is the distance between the plates. Electrostatic lines of force are strongest when the charged particles that create them are close together. When the charged particles are moved further apart, the lines of force are weakened and the ability to store a charge decreases.

7-13. The third factor affecting capacitance is the dielectric constant of the insulating material between the plates of a capacitor. The various insulating materials used as the dielectric in a capacitor differ in their ability to respond to (or pass) electrostatic lines of force. A dielectric material, or insulator, is rated as to its ability to respond to electrostatic lines of force in terms of a figure called the dielectric constant. A dielectric material with a high dielectric constant is a better insulator than a dielectric material with a low dielectric constant. Dielectric constants for some common materials are listed in Table 7-1.

7-14. Since a vacuum is the standard reference, it is assigned a dielectric constant of one. The dielectric constants for all other materials are compared to that of a vacuum. Since the dielectric constant for air has been determined to be about the same as for a vacuum, the dielectric constant of air is also considered to be equal to one.

Table 7-1. Dielectric Constants for Common Materials

Material	Constant
Vacuum	1.0000
Air	1.0006
Paraffin paper	2.5 – 3.5
Transformer oil	4
Glass	5 –10
Mica	3 – 6

Table 7-1. Dielectric Constants for Common Materials (continued)

Material	Constant
Rubber	2.5 – 35
Wood	2.5 – 8
Porcelain	6
Glycerin (15 C)	56
Petroleum	2
Pure water	81
Capacitor Rating	

CAPACITOR RATING

7-15. In selecting or substituting a capacitor for use, consideration must be given to the value of capacitance desired and the amount of voltage to be applied across the capacitor. If the voltage applied across the capacitor is too great, the dielectric will break down and arcing will occur between the capacitor plates. When this happens, the capacitor becomes a short circuit and the flow of current through it causes damage to other electrical components. A capacitor is not a conductor. It is used as a power source that delivers current to the circuit at a different time than it would have originally received it. Each capacitor has a voltage rating (a working voltage) that should never be exceeded.

7-16. The working voltage of a capacitor is the maximum voltage that can be steadily applied without danger of breaking down the dielectric. The working voltage depends on the type of material used as the dielectric and on the thickness of the dielectric. A high-voltage capacitor that has a thick dielectric must have a relatively large plate area to have the same capacitance as a similar low-voltage capacitor having a thin dielectric. The working voltage also depends on the applied frequency because losses and the resultant heating effect increase as the frequency increases.

EXPEDIENT REPLACEMENT

7-17. Certain expedient capacitor replacements can be made in the event of an electrical casualty on a single-phase motor. The following is a guide for capacitor replacement when the exact replacement part is unavailable.

7-18. A start capacitor can be replaced with another capacitor equal to but not greater than 20 percent of the original microfarad rating. The voltage rating must be equal to or greater than the original capacitor voltage rating. A run capacitor can be replaced with another capacitor within plus or minus 10 percent of the original microfarad rating. The voltage rating must be equal to or greater than the original capacitor voltage rating. A capacitor that may be safely charged to 500 volts DC cannot be safely subjected to an alternating voltage or a pulsating direct voltage having the same effective value of 500 volts. In practice, select a capacitor so that its working voltage is at least 50 percent greater than the highest effective voltage applied to it.

CAPACITOR LOSSES

7-19. Power loss in a capacitor may be attributed to dielectric hysteresis and dielectric leakage. Dielectric hysteresis is an effect in a dielectric material similar to the hysteresis found in a magnetic material. It is the result of changes in orientation of electron orbits in the dielectric because of the rapid reversals of the polarity of the line voltage. The amount of power loss due to dielectric hysteresis depends on the type of dielectric used. A vacuum dielectric has the smallest power loss.

7-20. Dielectric leakage occurs in a capacitor as the result of current leaking through the dielectric. It is normally assumed that the dielectric will effectively prevent the flow of current through the capacitor. Although the resistance of the dielectric is extremely high, a small amount of current does flow. Ordinarily this current is so small that for all practical purposes it is ignored. However, if the leakage through the dielectric is abnormally high, there will be a rapid loss of charge and an overheating of the capacitor.

7-21. The power loss of a capacitor is determined by loss in the dielectric. If the loss is negligible and the capacitor returns the total charge to the circuit, it is considered to be a perfect capacitor with a loss of zero.

CHARGING AND DISCHARGING A CAPACITOR

7-22. To better understand the action of a capacitor in conjunction with other components, the charge and discharge actions of a purely capacitive circuit are analyzed first. For ease of explanation, the capacitor and voltage source in Figure 7-6 are assumed to be perfect (no internal resistance), although this is impossible in practice.

CHARGING

7-23. Figure 7-6, view A, shows an uncharged capacitor connected to a four-position switch. With the switch in position 1, the circuit is open and no voltage is applied to the capacitor. Initially, each plate of the capacitor is a neutral body. Until a difference in potential is impressed (or a voltage applied) across the capacitor, no electrostatic field can exist between the plates.

7-24. To charge the capacitor, the switch must be thrown to position 2, which places the capacitor across the terminals of the battery. Under the assumed perfect conditions, the capacitor would reach full charge instantaneously. However, in the following discussion, the charging action is spread out over a period of time for a step-by-step analysis.

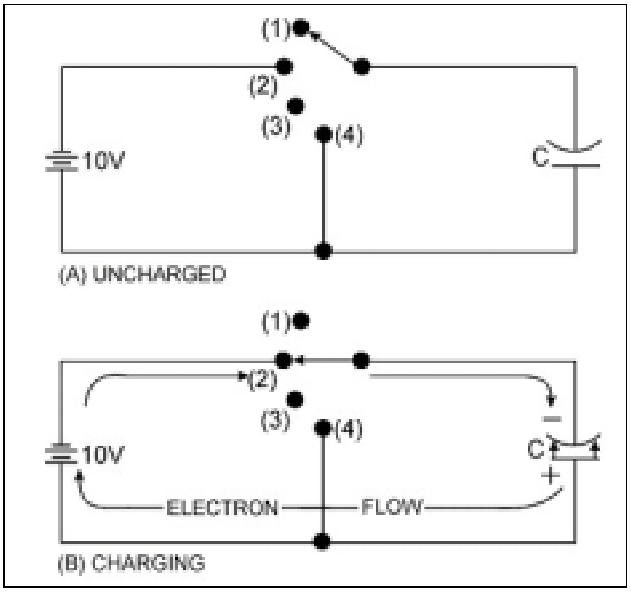

Figure 7-6. Charging a Capacitor

7-25. At the instant the switch is thrown to position 2 (see Figure 7-6, view B), a displacement of electrons occurs simultaneously in all parts of the circuit. This electron displacement is directed away from the negative terminal and toward the positive terminal of the source (the battery). A brief surge of current will flow as the capacitor charges. If it were possible to analyze the motion of individual electrons in this surge of charging current, the action described below would be observed (see also Figure 7-7).

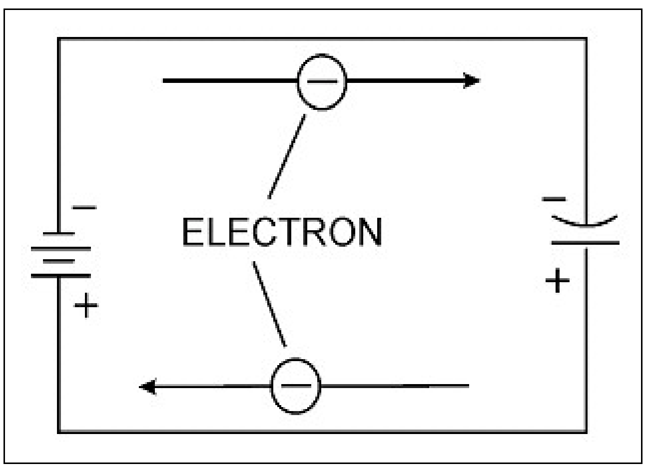

Figure 7-7. Electron Motion During Charge

7-26. At the instant the switch is closed, the positive terminal of the battery extracts an electron from the bottom conductor. The negative terminal of the battery forces an electron into the top conductor. At this same instant, an electron is forced into the top plate of the capacitor and another is pulled from the bottom plate. Therefore, in every part of the circuit, a clockwise displacement of electrons occurs simultaneously.

7-27. As electrons accumulate on the top plate of the capacitor and others depart from the bottom plate, a difference of potential develops across the capacitor. Each electron forced onto the top plate makes that plate more negative, while each electron removed from the bottom causes the bottom plate to become more positive. The polarity of the voltage that builds up across the capacitor is such as to oppose the source voltage. The source voltage (EMF) forces current around the circuit of Figure 7-7 in a clockwise direction. However, the EMF developed across the capacitor has a tendency to force the current in a counterclockwise direction, opposing the source EMF. As the capacitor continues to charge, the voltage across the capacitor rises until it is equal to the source voltage. Once the capacitor voltage equals the source voltage, the two voltages balance one another and current ceases to flow in the circuit.

7-28. In the charging process of a capacitor, no current flows through the capacitor. The material between the plates of the capacitor is an insulator. However, to an observer stationed at the source or along one of the circuit conductors, the action appears to be a true flow of current even though the insulating material between the plates of the capacitor prevents the current from having a complete path. The current that appears to flow through a capacitor is called displacement current.

7-29. When a capacitor is fully charged and the source voltage is equaled by the CEMF across the capacitor, the electrostatic field between the plates of the capacitor is maximum (see Figure 7-4). Since the electrostatic field is maximum, the energy stored in the dielectric field is maximum.

7-30. If the switch is opened (see Figure 7-8, view A), the electrons on the upper plate are isolated. The electrons on the top plate are attracted to the charged bottom plate. Since the dielectric is an insulator, the electrons cannot cross the dielectric to the bottom plate. The charges on both plates will be effectively trapped by the electrostatic field and the capacitor will remain charged. However, the insulating dielectric material of a practical capacitor is not perfect, so small leakage current will flow through the dielectric. This current will eventually dissipate the charge. A high quality capacitor may hold its charge for a month or more.

7-31. In review, when a capacitor is connected across a voltage source, a surge of charging current flows. This charging current develops a CEMF across the capacitor that opposes the applied voltage. When the capacitor is fully charged, the CEMF equals the applied voltage and charging current ceases. At full charge, the electrostatic field between the plates is at maximum intensity and the energy stored in the dielectric is maximum. If the charged capacitor is disconnected from the source, the charge will be retained for some time. The length of time the charge is retained depends on the amount of leakage current present. Since electrical energy is stored in the capacitor, a charged capacitor can act as a source EMF.

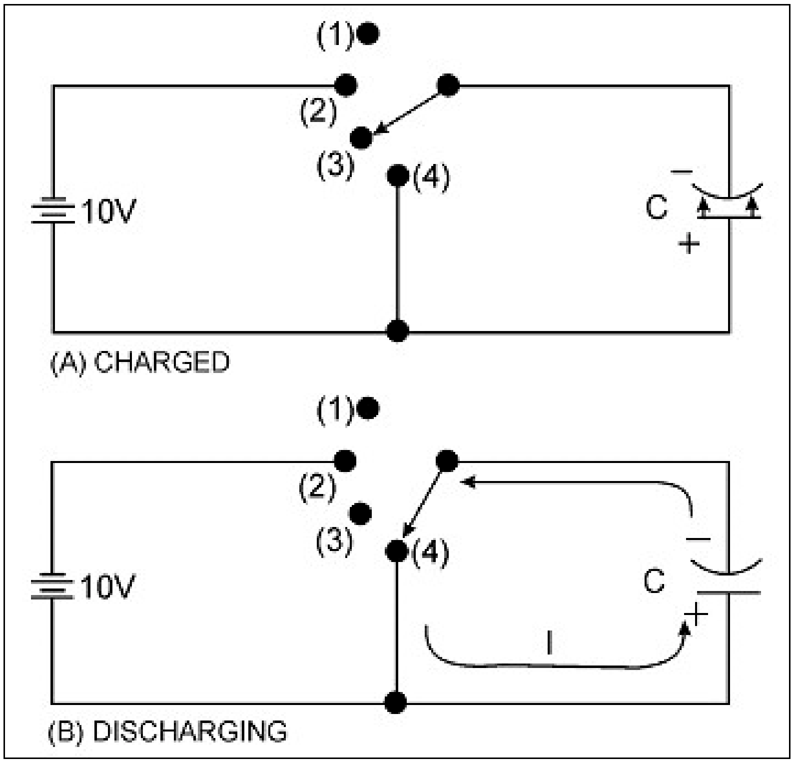

Figure 7-8. Discharging a Capacitor

DISCHARGING

7-32. To discharge a capacitor, the charges on the two plates must be neutralized. This is done by providing a conducting path between the two plates (see Figure 7-8, view B). With the switch in position (4), the excess electrons on the negative plate can flow to the positive plate and neutralize its charge. When the capacitor is discharged, the distorted orbits of the electrons in the dielectric return to their normal positions and the stored energy is returned to the circuit. A capacitor does not consume power. The energy the capacitor draws from the source is recovered when the capacitor is discharged.

CHARGE AND DISCHARGE OF A CAPACITOR

7-33. Ohm's law states that the voltage across a resistance is equal to the current through the resistance times the value of the resistance. This means that a voltage is developed across a resistance only when current flows through a resistance.

7-34. A capacitor can store or hold a charge of electrons. When uncharged, both plates of the capacitor contain essentially the same number of free electrons. Also when charged, one plate contains more free electrons than the other plate. The difference in the number of electrons is a measure of the charge on the capacitor. The accumulation of this charge builds up a voltage across the terminals of the capacitor and the charge continues to increase until this voltage equals the applied voltage.

The charge in a capacitor is related to the capacitance and voltage as follows:

$$Q = CE$$

Where:

Q = charge in coulombs

C = capacitance in farads

E = EMF across the capacitor in volts

CAPACITORS IN SERIES AND IN PARALLEL

7-35. Capacitors may be connected in series or in parallel to obtain a resultant value. This value may be either the sum of the individual values (in parallel) or a value less than that of the smallest capacitance (in series).

CAPACITORS IN SERIES

7-36. The overall effect of connecting capacitors in series is to move the plates of the capacitor farther apart. A capacitor is not a conductor. The dielectric is influenced by a magnetic field and the polarity that creates the electrostatic field can effectively exist only at the outside plates of both capacitors. The magnetic field's influence is reduced (see Figure 7-9). In the figure, the junction between C_1 and C_2 is essentially neutral. The total capacitance of the circuit is developed between the leftmost plate of C_1 and the rightmost plate of C_2. Since these outside plates are so far apart, the total value of the capacitance in the circuit is decreased. Solving for the total capacitance (C_T) of capacitors connected in series is similar to solving for the total resistance (R_T) of resistors connected in parallel.

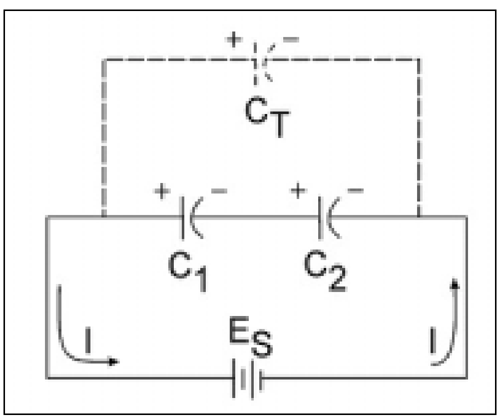

Figure 7-9. Capacitors in Series

7-37. Note the similarity between the formulas for R_T and C_T:

$$R_T = \cfrac{1}{\cfrac{1}{R_1} + \cfrac{1}{R_2} + \cfrac{1}{\ldots R_n}}$$

$$C_T = \cfrac{1}{\cfrac{1}{C_1} + \cfrac{1}{C_2} + \cfrac{1}{\ldots C_n}}$$

If the circuit contains more than two capacitors, use the above formulas. If the circuit contains only two capacitors, use the following formula:

$$C_T = \frac{(C_1) \times (C_2)}{C_1 + C_2}$$

Note: All values for C_T, (for example, C_1, C_2, C_3, . . . C_n) should be in farads. It should be evident from the above formulas that the total capacitance of capacitors in series is less than the capacitance of any of the individual capacitors.

CAPACITORS IN PARALLEL

7-38. When capacitors are connected in parallel, one plate of each capacitor is connected directly to one terminal of the source, while the other plate of each capacitor is connected to the other terminal of the power source. Figure 7-10 shows all the negative plates of the capacitors connected together and all the positive plates connected together. Therefore, C_T appears as a capacitor with a plate area equal to the sum of all the individual plate areas. Capacitance is a direct function of plate area. Connecting capacitors in parallel effectively increases plate area and thereby increases total capacitance.

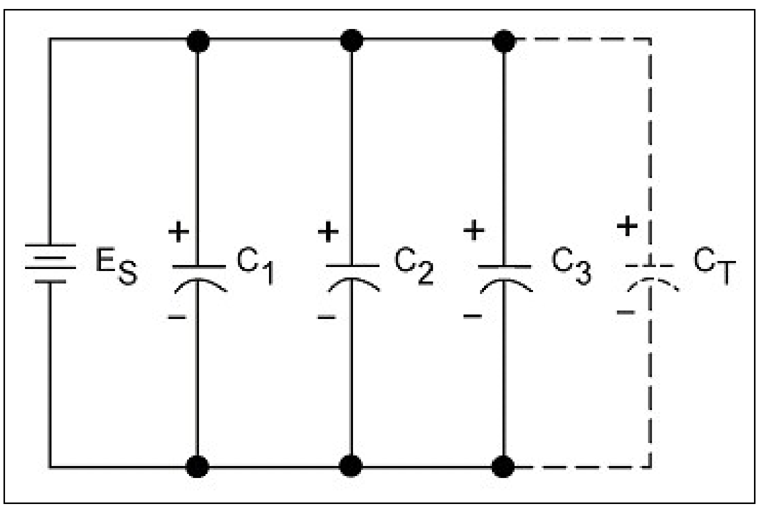

Figure 7-10. Parallel Capacitive Circuit

7-39. For capacitors connected in parallel, the total capacitance is the sum of all the individual capacitors. The total capacitance of the circuit may be calculated using the following formula:

$$C_T = C_1 + C_2 + C_3 + \ldots C_n$$

In the above formula, all capacitances are in the same units.

FIXED CAPACITOR

7-40. A fixed capacitor is constructed so that it possesses a fixed value of capacitance, which cannot be adjusted. A fixed capacitor is classified according to the type of material used as its dielectric (such as paper, oil, mica, or electrolyte). Two capacitors commonly found in the marine field are the electrolytic capacitor and the paper capacitor.

ELECTROLYTIC CAPACITOR

7-41. The electrolytic capacitor is used where a large amount of capacitance is required. As the name implies, an electrolytic capacitor contains electrolyte. This electrolyte can be in the form of a liquid (wet electrolytic capacitor). The wet electrolytic capacitor is no longer in popular use because of the care needed to prevent spilling of the electrolyte.

7-42. A dry electrolytic capacitor consists essentially of two metal plates separated by the electrolyte. The capacitance values and the voltage ratings of the capacitor are generally printed on the side of the case.

7-43. Internally, the electrolytic capacitor is almost constructed the same as the paper capacitor. The positive plate consists of aluminum foil covered with an extremely thin film of oxide. This thin oxide film, which is formed by an electrochemical process, acts as the dielectric of the capacitor. Next to and in contact with the oxide strip is paper or gauze that has been impregnated with a paste-like electrolyte. The electrolyte acts as the negative plate of the capacitor. A second strip of aluminum foil is then placed against the electrolyte to provide electrical contact to the negative electrode. When the three layers are in place, they are rolled up into a cylinder (see Figure 7-11).

7-44. The following are two disadvantages of the DC electrolytic capacitor compared to a paper capacitor:

- The electrolyte type is polarized.
- The electrolyte type has a low-leakage resistance.

This means that should the positive plate be accidentally connected to the negative terminal of the source, the thin oxide film dielectric will dissolve and the capacitor will become a conductor (this means, it will short). These electrolytic capacitors are very common in DC systems. DC electrolytic capacitors have the polarity indicated on the casing or capacitor terminals. Observe the polarity so that they are never connected into an AC circuit.

WARNING

The electrolytic capacitor could explode if the precautions described in the preceding paragraph are not observed.

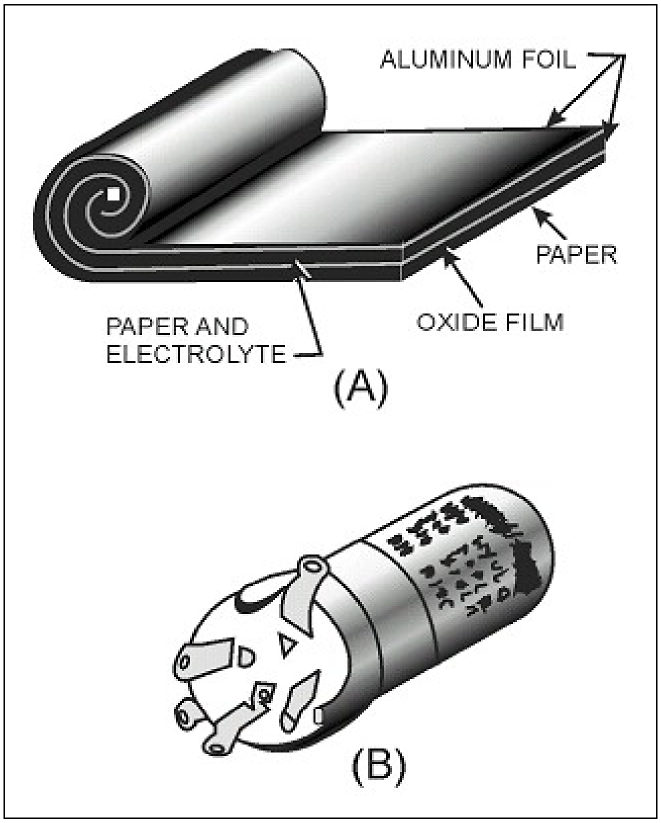

Figure 7-11. Construction of an Electrolytic Capacitor

7-45. The AC electrolytic capacitor has been specially developed for single-phase AC motors. These capacitors, which are generally encased in plastic, are called start capacitors. They have 20 times the capacitance of motor-run capacitors. The start capacitors are small in size and high in capacitance. Not intended for constant use, the start capacitor can be readily removed from the motor's starting circuit after a short time.

7-46. These AC capacitors effectively provide a two-phase current to the single-phase motor. This is done by allowing the initial source current to arrive in one winding before it arrives in the other single-phase motor windings.

PAPER CAPACITOR

7-47. A paper capacitor is made of flat thin strips of metal foil conductors that are separated by waxed paper (the dielectric material). Paper capacitors usually range in value from about 300 picofarads to about 4 microfarads. The working voltage of a paper capacitor rarely exceeds 600 volts. Paper capacitors are sealed with wax to prevent corrosion, leakage, and the harmful effects of moisture.

7-48. Many different kinds of outer coverings are used on paper capacitors. The simplest is a tubular cardboard covering. Some paper capacitors are encased in very hard plastic. These types are very rugged and can be used over a much wider temperature range than can the tubular cardboard type. Figure 7-12 shows the construction of a tubular paper capacitor.

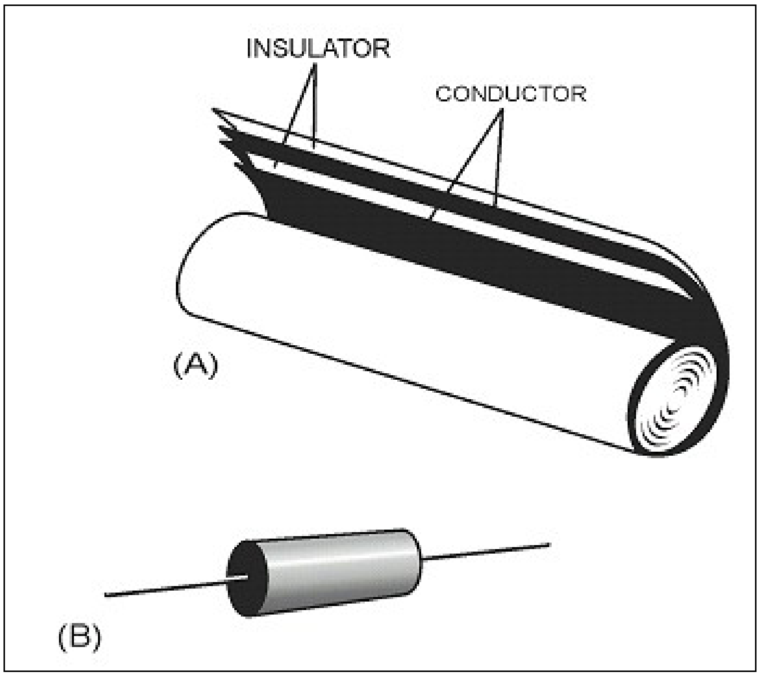

Figure 7-12. Paper Capacitor

7-49. Paper capacitors are generally used for run capacitors in single-phase motors. These capacitors are metal-cased and have a low capacitance for constant operation in the AC circuit. The larger size and lower capacitance is necessary for effective heat transfer.

7-50. Oil capacitors are often used in high-power electrical equipment. An oil-filled capacitor is nothing more than a paper capacitor immersed in oil. Since oil-impregnated paper has a high dielectric constant, it can be used to produce capacitors with a high capacitance value. Many capacitors will use oil with another dielectric material to prevent arcing between plates. If arcing should occur between the plates of an oil-filled capacitor, the oil will tend to reseal the hole caused by the arcing. Such a capacitor is called a self-healing capacitor.

7-51. Polychlorinated biphenyl or PCBs were commonly used to impregnate capacitors. This oil is used as a lubricant (for heat transfer) and as a fluid for a tire-resistant application. PCBs are toxic. If a capacitor is leaking, remove it from the circuit immediately. Personnel should not come in contact with the liquid.

WARNING

Treat material leaking from a capacitor as if it is a very hazardous material and dispose of it according to local regulations.

CAPACITIVE AND INDUCTIVE REACTANCE

7-52. When the voltage and current values are changing together through a cycle so that the values begin, peak, and change direction together, they are in phase. When these same values fail to stay in phase because one value leads or lags the other value, the circuit is said to be out of phase. The deviation from the simultaneous starting, peaking, and directional change of in-phase values is a direct result of the effects capacitance and inductance have on the circuit.

7-53. A circuit having pure resistance (if such a circuit could exist) would have the AC and voltage rising, falling, and changing direction together. Figure 7-13, view A, shows the sine waves for current and voltage in a purely resistive AC circuit. The voltage and current do not have the same amplitude, but they are in phase.

7-54. In the case of a circuit having inductance, the opposing force of the CEMF would be enough to prevent the current from remaining in phase with the applied voltage. In a DC circuit containing pure inductance, the current would take time to rise to a maximum even though the full applied voltage was immediately at maximum.

7-55. Figure 7-13, view B, shows the waveforms for a purely inductive AC circuit in steps of quarter-cycles. In the first quarter-cycle (0 to 90 degrees), the applied AC voltage is continually increasing. If there was no inductance in the circuit, the current would also increase during the first quarter-cycle. The circuit in Figure 7-13, view B, does have inductance. Since inductance opposes any change in current flow, no current flows during the first quarter-cycle. In the next quarter-cycle (90 to 180 degrees), the voltage decreases back to zero. Current begins to flow in the circuit and reaches a maximum value at the same instant the voltage reaches zero. The applied voltage now begins to build up to a maximum in the other direction, to be followed by the resulting current. When the voltage again reaches its maximum at the end of the third quarter-cycle (270 degrees), all values are exactly opposite to what they were during the first half-cycle. The applied voltage leads the resulting current by one quarter-cycle or 90 degrees. To complete the full 360-degree cycle of the voltage, the voltage again decreases to zero, and current builds to a maximum value.

7-56. These values do not stop at a particular instant. Until the applied voltage is removed, current and voltage are always changing in amplitude and direction.

7-57. The sine wave can be compared to a circle (see Figure 7-14). Just as a circle can be marked off into 360 degrees, the time of one cycle of a sine wave can be marked off into 360 degrees. Figure 7-14 shows how the current lags the voltage by 90 degrees in a purely inductive circuit. Figure 7-13, view A and Figure 7-14 also shows how the current and voltage are in phase in a purely resistive circuit. In a circuit having resistance and inductance, the current lags voltage by an amount somewhere between 0 and 90 degrees.

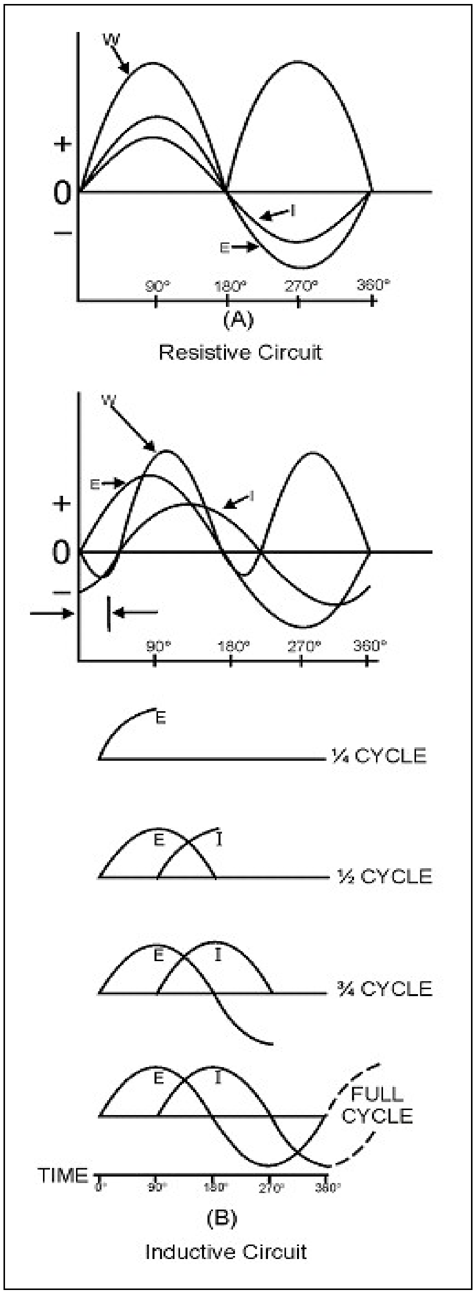

Figure 7-13. Voltage and Current Waveforms

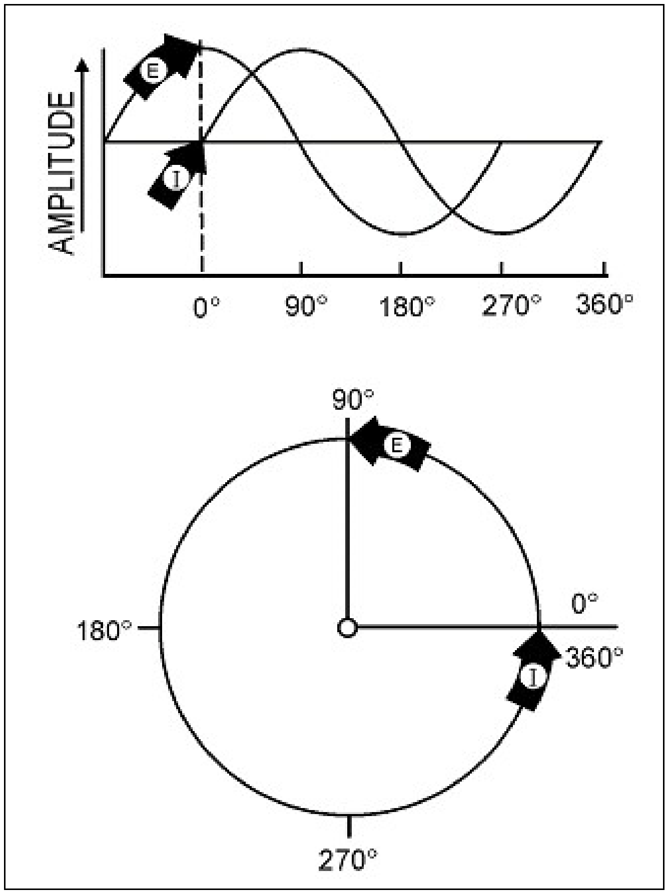

Figure 7-14. Comparison of Sine Wave and Circle in an Inductive Circuit

INDUCTIVE REACTANCE

7-58. When the current flowing through an inductor continuously reverses itself, as in the case of an AC system, the inertia of the CEMF is greater than with DC. The greater the amount of inductance, the greater the opposition from this inertia effect. Also, the faster the current reverses, the greater this inertial opposition. This opposing force that an inductor presents to the flow of AC cannot be called resistance, because it is not the result of friction within a conductor. The name given to it is inductive reactance because it is the reaction of the inductor to AC. Inductive reactance is measured in ohms and its symbol is XL.

7-59. The induced voltage in a conductor is proportional to the rate at which magnetic lines of force cut the conductor. The greater the rate (the higher the frequency), the greater the CEMF. Also, the induced voltage increases with an increase in inductance; the more ampere-turns, the greater the CEMF. Reactance then increases with an increase of inductance.

CAPACITORS AND ALTERNATING CURRENT

7-60. Figure 7-15 shows the four parts of the variation of the alternating voltage and current in a capacitive circuit for each quarter cycle. The solid line represents the voltage across the capacitor and the dotted line represents the current. The line running through the center is the zero, or reference point, for voltage and current. The bottom line marks off the time of the cycle in terms of electrical degrees. Assume that the AC voltage has been acting on the capacitor for some time before the time represented by the starting point of the sine wave in the figure.

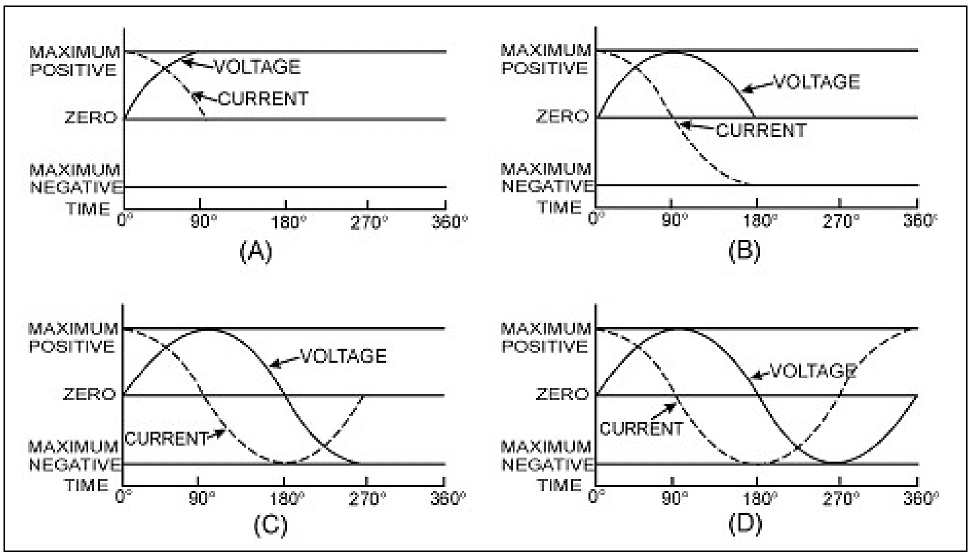

Figure 7-15. Phase Relationship of Voltage and Current in a Capacitive Circuit

7-61. At the beginning of the first quarter-cycle (0 to 90 degrees), the voltage has just passed through zero and is increasing in the opposite direction. Since the zero point is the steepest part of the sine wave, the voltage is changing at its greatest rate. The charge on a capacitor varies directly with the voltage. Therefore, the charge on the capacitor is also changing at its greatest rate at the beginning of the first quarter-cycle. In other words, the greatest number of electrons are moving off one plate and onto the other plate. Therefore, the capacitor current is at its maximum value (see Figure 7-15, view A).

7-62. As the voltage proceeds toward maximum at 90 degrees, its rate of change becomes less and less. Therefore, the current must decrease toward zero. At 90 degrees, the voltage across the capacitor is maximum and the capacitor is fully charged. There is no further movement of electrons from plate to plate. That is why the current at 90 degrees is zero.

7-63. At the end of the first quarter-cycle, the alternating voltage stops increasing in the positive direction and starts to decrease. It is still a positive voltage, but to the capacitor, the decrease in voltage means that the plate that has just accumulated an excess of electrons must lose some electrons. The current flow must reverse its direction. Figure 7-15, view B, shows the current to be below the zero line (negative current direction) during the second quarter-cycle (90 to 180 degrees).

7-64. At 180 degrees, the voltage has dropped to zero. This means that for a brief instant the electrons are equally distributed between the two plates. The current is maximum because the rate of change of voltage is maximum. Just after 180 degrees, the voltage has reversed polarity and starts building up its maximum negative peak, which is reached at the end of the third quarter-cycle (180 to 270 degrees). During this third quarter-cycle, the rate of voltage change gradually decreases as the charge builds to a maximum at 270 degrees. At this point, the capacitor is fully charged and carries the full impressed voltage. With the capacitor fully charged, there is no further exchange of electrons. Therefore, the current flow is zero at this point. The conditions are exactly the same as at the end of the first quarter-cycle (90 degrees), but the polarity is reversed.

7-65. Just after 270 degrees, the impressed voltage once again starts to decrease and the capacitor must lose electrons from the negative plate. It must discharge, starting at a minimum rate of flow and rising to a maximum. This discharging action continues through the last quarter-cycle (270 to 360 degrees) until the impressed voltage has reached zero. At 360 degrees, it is back at the beginning of the entire cycle and the AC cycle starts over again.

7-66. Figure 7-15, view D, shows that the current always arrives at a certain point in the cycle 90 degrees ahead of the voltage because of the charging and discharging action. This time and place relationship between the current and voltage is called the phase relationship. The voltage-current phase relationship in a capacitive circuit is exactly opposite to that of an inductive circuit. The current through a capacitor leads voltage across the capacitor by 90 degrees.

7-67. The current and voltage are going through their individual cycles at the same time during the period the AC voltage is impressed. The current does not go through part of its cycle (charging or discharging), stop, and wait for the voltage to catch up. The amplitude and polarity of the voltage and the amplitude and direction of the current are continually changing. Their positions with respect to each other and to the zero line at any electrical instant (any degree between 0 and 360) can be seen by reading vertically from the time-degree line in view D. The current swing from the positive peak at 0 degrees to the negative peak at 180 degrees is not a measure of the number of electrons or the charge on the plates. It is a picture of the direction and strength of the current relationship to the polarity and strength of the voltage appearing across the plates.

7-68. Since the plates of the capacitor are changing polarity at the same rate as the AC voltage, the capacitor seems to pass an AC. Actually, the electrons do not pass through the dielectric, but their rushing back and forth from plate to plate causes a current flow in the circuit. It is convenient to say that the AC flows through the capacitor. This is not true, but the expression avoids confusion when speaking of current flow in a circuit containing a capacitor.

IMPEDANCE

7-69. Inductive reactance and capacitive reactance act to oppose the flow of current in an AC circuit. However, another factor, the resistance, also opposes the flow of current. Since in practice, AC circuits containing reactance also contain resistance, the two combine to oppose the flow of current. This combined opposition by the resistance and the reactance is called the impedance and is represented by the symbol Z.

7-70. Since the values of resistance and reactance are given in ohms, it might at first seem possible to determine the value of the impedance by simply adding them together. However, it cannot be done so easily. In an AC circuit that contains only resistance, the current and voltage will be in step (in phase) and will reach their maximum values at the same instant. Also, in an AC circuit containing only reactance, the current will either lead or lag the voltage by 90 degrees. When reactance and resistance are combined, the value of the impedance will be greater than either. It is also true that the current will not be in phase with the voltage nor will it be exactly 90 degrees out of phase with the voltage. It will be somewhere between the in-phase and the 90 degree out-of-phase condition. The larger the reactance compared with the resistance, the more nearly the phase angle will approach 90 degrees. The larger the resistance compared to the reactance, the more nearly the phase difference will approach 0 degrees.

CAPACITANCE

Questions

1. What is the name of the invisible lines of force surrounding any charged particle?
2. How is an electrostatic field polarized?
3. The ability of an electrostatic field to attract and repel charges allows the capacitor to do what?
4. What is the name of the insulating material that separates the two metal plates in a simple capacitor?
5. What is the reason the orbits of the electrons are distorted in the electrostatic field?
6. Capacitance is measured in units call what?
7. What three factors affect the value of the capacitance of a capacitor?
8. What happens if the voltage across the capacitor is too great?
9. With what can a start capacitor be replaced?
10. With what can a run capacitor be replaced?
11. What is attributed to power loss in a capacitor?
12. What is the name of the current that appears to flow through a capacitor during the charging process?
13. How are capacitors connected to obtain a resultant value?
14. How is a fixed capacitor classified?
15. What type of capacitor is used in high-power electrical equipment?
16. When are voltage and current values in phase?
17. The time of one cycle of a sine wave can be marked off by how many degrees?
18. How is inductive reactance measured?
19. What is the name of the steepest part of the sine wave?
20. What is impedance?

Chapter 8

Transformers

This chapter describes a basic transformer and its functions. It also explains the characteristics of several different types of transformers.

INTRODUCTION TO TRANSFORMERS

8-1. A transformer is a device that transfers electrical energy from one circuit to another by electromagnetic induction (also called transformer action). It is most often used to step up or step down voltage. It is also occasionally used as an isolating device to eliminate a direct mechanical electrical connection between the power source and the loads. The electrical energy is always transferred without a change in frequency. However, it may involve changes in the effective value of voltage and current. Since a transformer works on the principle of electromagnetic induction, it must be used with an input source that varies in amplitude.

8-2. Examining a very unusual transformer will show that power is transferred through the use of electromagnetic induction. This DC transformer will demonstrate the actions of a step-up transformer and provide stop-action analysis of the moving magnetic field. Figure 8-1 shows a one-line diagram of the primary and secondary automobile ignition system. The primary circuit, or power source side, includes the following:

- Battery positive terminal.
- Ignition switch.
- Primary winding to the ignition points.
- Battery negative terminal.

The secondary circuit begins with the secondary winding wire and connects the distributor rotor and the spark plug.

8-3. When both the ignition switch and the points are closed, there is a complete circuit through the 12-volt battery terminals and the primary windings. As a current initially moves through the conductor, an expanding magnetic field is created. As the magnetic field from the primary winding expands across the secondary windings, a type of generator is created that produces an EMF in the secondary windings. Through electromagnetic induction, the secondary winding has all the necessities for generating the following:

- An EMF conductor (the secondary winding).
- The magnetic field (from the current flow through the primary winding).
- The relative motion between the expanding magnetic field and the secondary winding.

As the contact points open, the primary field collapses. With this collapse, there is again relative motion between the magnetic field and the secondary windings. This motion and the increased number of conductors in the secondary windings allow the coil to step up voltage from the original 12 volts to the 20,000 volts necessary to fire this type of ignition system.

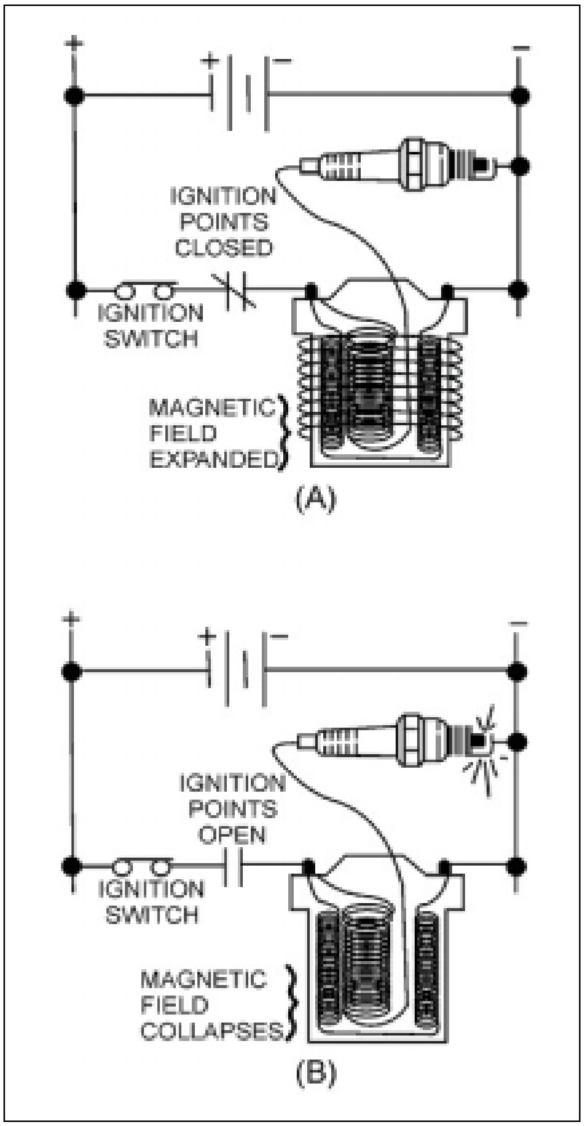

Figure 8-1. Automobile Step-Up Transformer

8-4. The distributor, ignition points, and condenser that make up this DC switching device are very costly. It is not very practical to use DC to step up voltage. AC has certain advantages over DC because it changes direction readily and has a constantly moving magnetic field. One important advantage of using AC is that the voltage and current levels can be increased or decreased by means of a transformer.

BASIC OPERATION OF A TRANSFORMER

8-5. The transformer circuit in Figure 8-2 shows basic transformer action. The primary winding is connected to a 60 hertz AC source. The magnetic field (flux) expands and collapses about the primary winding. The expanding and contracting magnetic field around the primary winding cuts the secondary winding and induces an EMF into the winding. When a circuit is completed between the secondary winding and a load, this voltage causes current to flow. The voltage may be stepped up or down depending on the number of turns of the conductor in the primary and secondary windings.

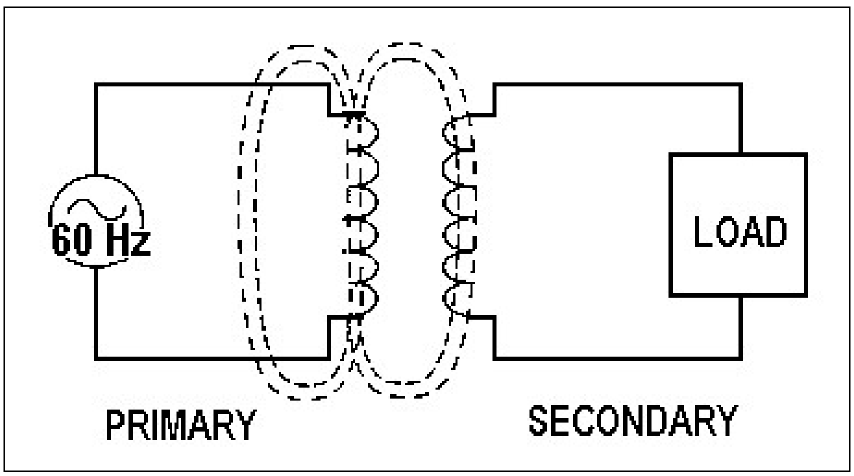

Figure 8-2. Basic Transformer Action

8-6. The ability of a transformer to transfer power from one circuit to another is excellent. For marine engineering applications, the power loss is negligible. Power into the transformer is considered equal to power out. It is possible to increase, or step up, the voltage to loads with a subsequent reduction in current. The power formula (P = I x E) demonstrates this phenomenon. The transformer is rated by power or VA for volts times amps. Transformers are rated more often in kVA for thousands of volt amps. The terms “step up” or “step down” refer to the actions of the voltage. A step-down transformer means that the voltage of the source has been reduced to a lesser value for the loads.

8-7. Examples of step-down transformers can be found on most Army watercraft. The ship service generator provides 450 VAC to the distribution system. The lighting panels and smaller motors require 115 VAC for a power supply. The ship’s transformers step down the 450 volts to 115 volts. Although there is less voltage in the load side than in the power supply side, the current in the load side will be greater than the current provided from the source side. For example, if the ship service generator provides 450 VAC at 20 amperes to the primary winding of the transformer, the secondary winding of the transformer will provide 115 VAC at 78 amperes to the loads.

Primary (generator) side:

$$P = I \times E$$

$$P = 20 \text{ amps} \times 450 \text{ volts}$$

$$P = I \times E \quad \text{or} \quad I = \frac{P}{E}$$

$$I = \frac{9{,}000 \text{ VA}}{115 \text{ volts}}$$

$$P = 9{,}000 \text{ VA (or 9 kVA)}$$

Secondary (load) side:

$$P = I \times E \quad \text{or} \quad I = \frac{P}{E}$$

$$I = \frac{9{,}000 \text{ VA}}{115 \text{ volts}}$$

$$I = 78 \text{ amps}$$

8-8. The conventional constant-potential transformer is designed to operate with the primary connected across a constant-potential source, such as the AC generator. It provides a secondary voltage that is substantially constant from no load to full load. Transformers require little care and maintenance because of their simple, rugged, and durable construction.

APPLICATIONS OF TRANSFORMERS

8-9. Various types of small, single-phase transformers are used in electrical equipment. In many installations, transformers are used in switchboards to step down the voltage for indicating lights. Low-voltage transformers are included in some motor control panels to supply control circuits or to operate contractors and relays.

8-10. Instrument transformers include potential or voltage transformers and current transformers. Instrument transformers are commonly used with AC instruments when high voltages or large currents are to be measured.

TRANSFORMER COMPONENTS

8-11. The principle parts of a transformer and their functions are—

- The core, which provides a path for the magnetic lines of flux.
- The primary winding, which receives power from the AC power source.

- The secondary winding, which receives power from the primary winding and delivers it to the load.
- The enclosure, which protects the above components from dirt, moisture, and mechanical damage.

CORE CHARACTERISTICS

8-12. The composition of a transformer core depends on such factors as voltage, current, and frequency. Size limitations and construction costs are also factors to be considered. Commonly used core materials are air, soft iron, and steel. Each of these materials is suitable for particular applications and unsuitable for others. Air-core transformers are generally used when the voltage source has a high frequency (above 20 kHz). Iron-core transformers are usually used when the source frequency is low (below 20 kHz). A soft-iron-core transformer is useful when the transformer must be physically small, yet efficient. The iron-core transformer provides better power transfer than does the air-core transformer. A transformer whose core is constructed of laminated sheets of steel dissipates heat readily, providing efficient transfer of power. Most transformers in the Army marine field contain laminated steel cores. These steel laminations (see Figure 8-3) are insulated with a nonconducting material (such as varnish) and then formed into a core. It takes about 50 such laminations to make a core an inch thick.

8-13. The laminations reduce certain losses that will be discussed later. The most effective transformer core is one that offers the best path for the most lines of flux with the least magnetic and electrical energy loss.

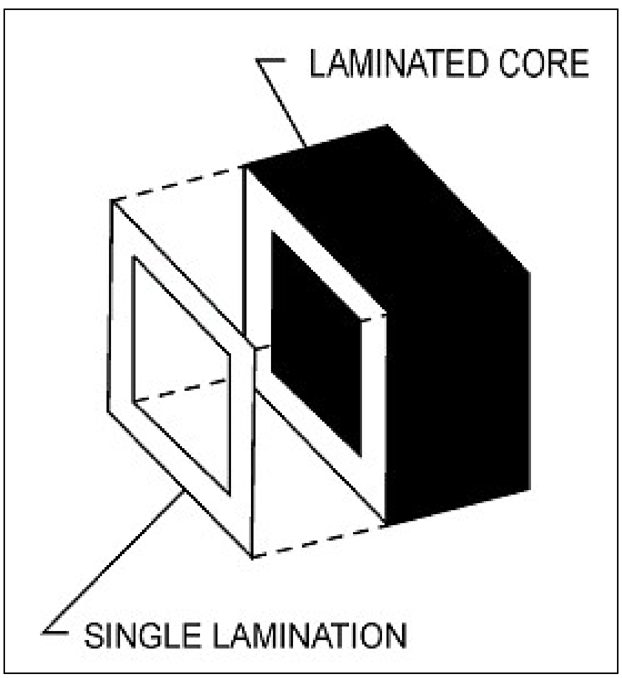

Figure 8-3. Hollow-Core Construction

8-14. Two main shapes of cores (hollow core and shell core) are used in laminated steel-core transformers. The hollow core is shaped with a square through the center (see Figure 8-3). The core is made up of many laminations of steel. Figure 8-4 shows how the transformer windings are wrapped around both sides of the core.

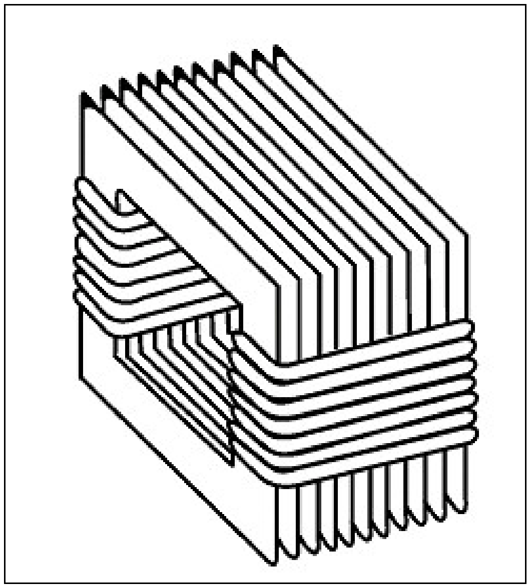

Figure 8-4. Windings Wrapped Around Laminations

The shell core is the most popular and efficient transformer (see Figures 8-5, 8-6, and 8-7).

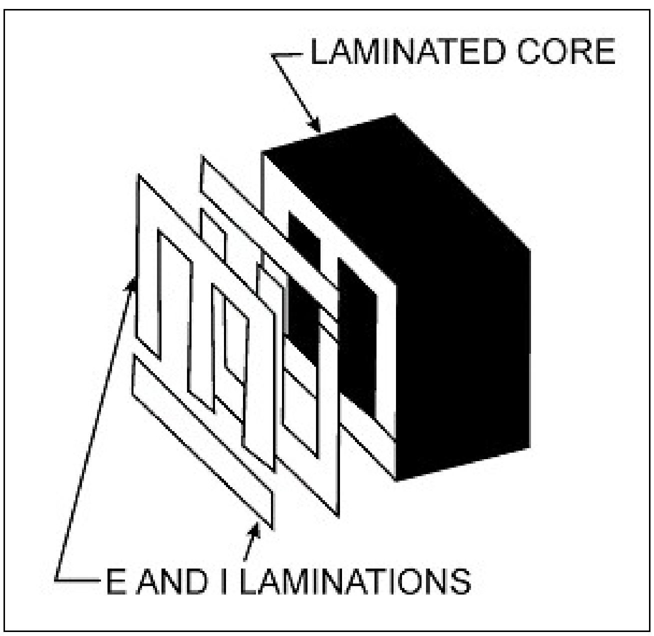

Figure 8-5. Shell-Type Construction

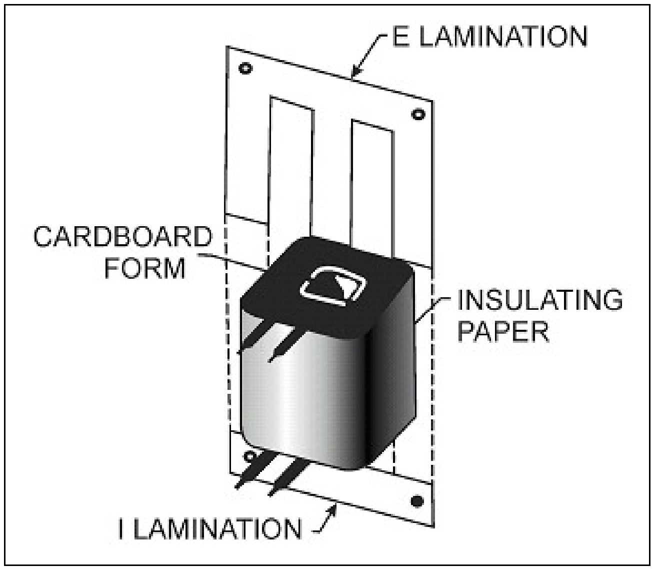

Figure 8-6. Exploded View of Shell-Type Transformer Construction

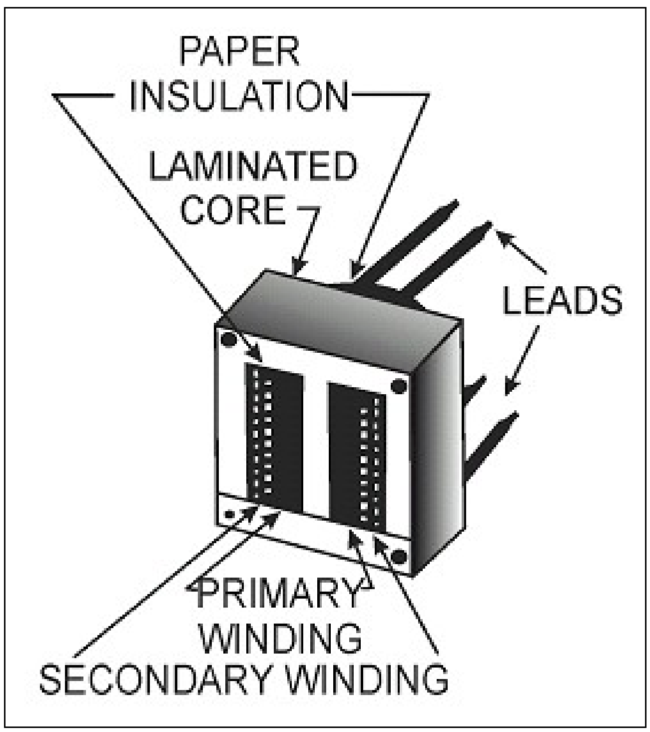

Figure 8-7. Cutaway View of Shell-Type Core With Windings

8-15. Figure 8-5 also shows that each layer of the core consists of E- and I-shaped sections of metal. These sections are butted together to form laminations. The laminations are insulated from each other and then pressed together to form a core.

TRANSFORMER WINDINGS

8-16. Two wires called windings are wound around the core. Each winding is electrically insulated from the other. The terminals are marked according to the voltage (H indicates the higher voltage and X indicates the lesser voltage). Figure 8-8 shows examples of these windings, with the voltages marked.

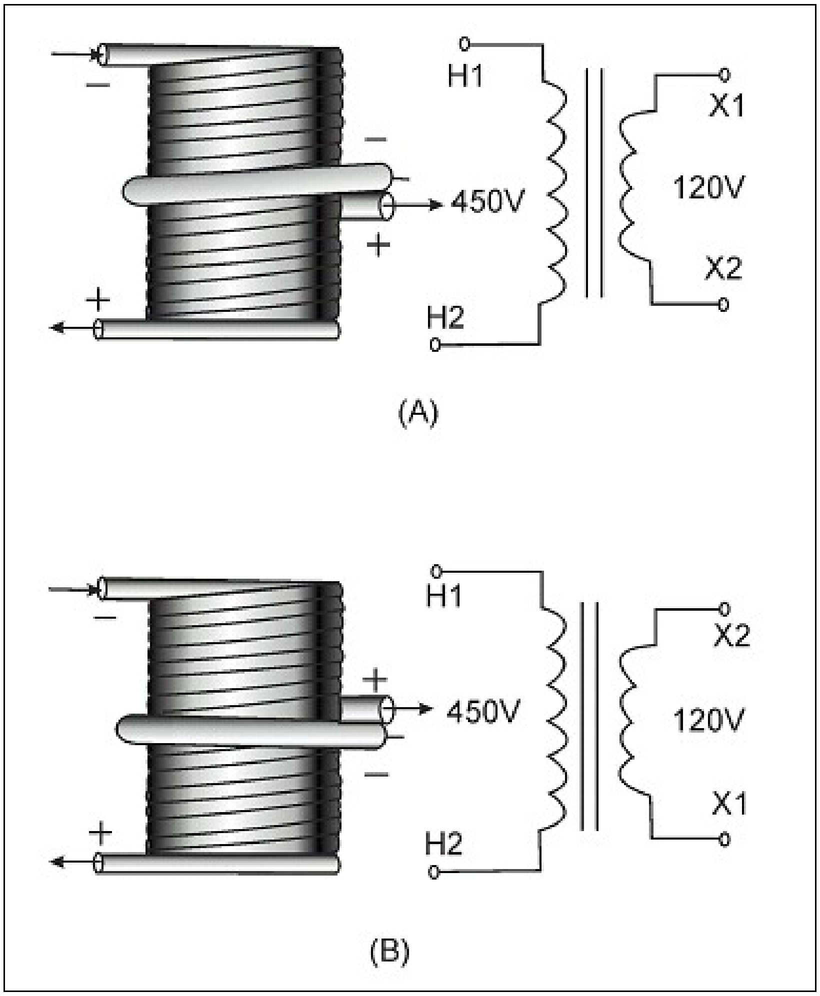

Figure 8-8. 450/120-Volt Step-Down Transformer

8-17. H1 and X1 also indicate polarity. Since the AC is constantly changing polarity, the H1 and X1 indicate that the polarities at both these terminals are identical during the same instant in time. At the same moment H1 has current moving through it in a given direction, the induced current through terminal X1 is moving in the same direction. When the H1 and the X1 are diagonally positioned, a condition known as additive polarity is formed (see Figure 8-9, view A). When H1 and X1 are directly opposite each other, a condition known as subtractive polarity is formed (see Figure 8-9, view B).

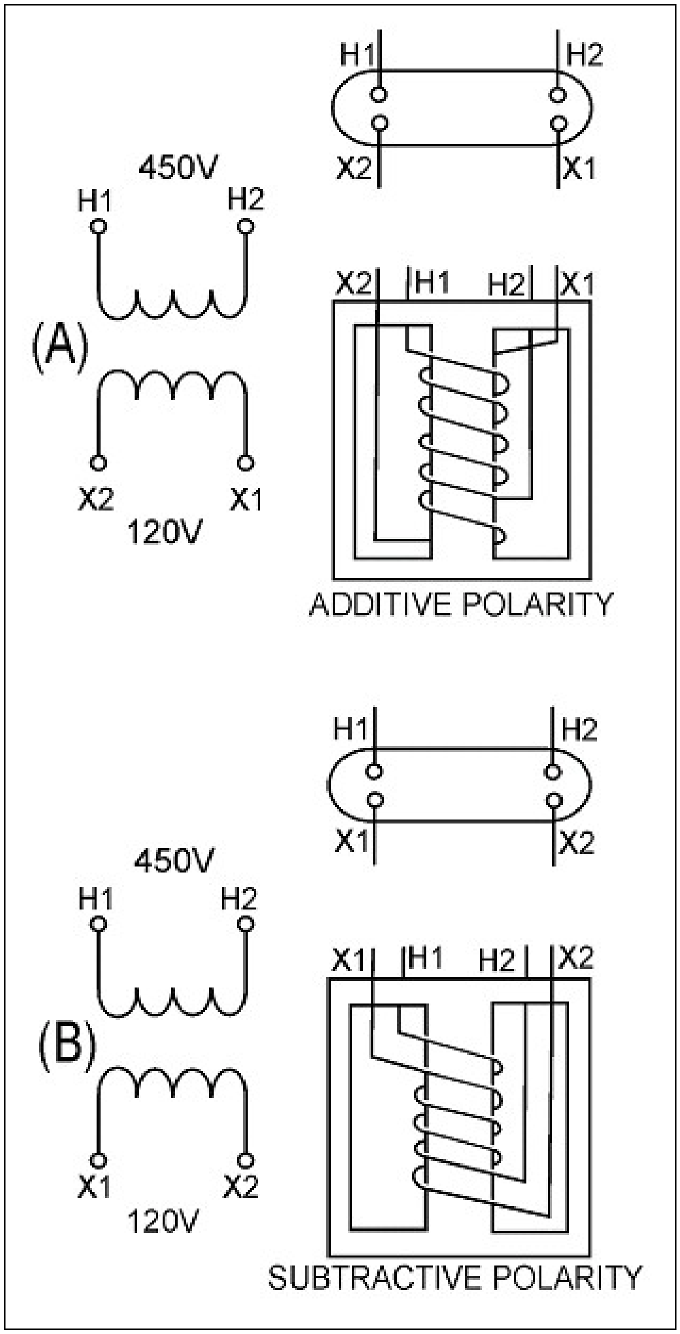

Figure 8-9. Polarity Markings for Large Transformers

8-18. Another way to mark polarity in schematic drawings is to use dot notation. Dots indicate which terminals are positive at the same instant in time. Figure 8-10 illustrates dot notation.

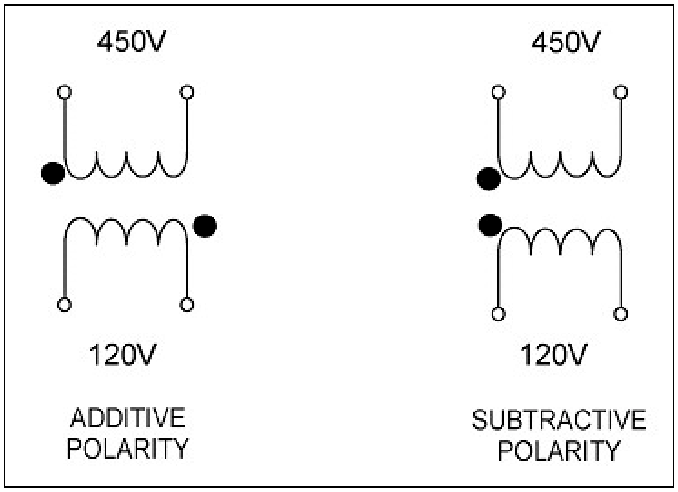

Figure 8-10. Instantaneous Polarity

8-19. All transformers are not wired the same way. Improper connections can damage the entire electrical circuit. The terms "additive polarity" and "subtractive polarity" come from the means of testing unmarked transformers. Do not connect a transformer opposite to its intended purpose. Do not connect a step-down transformer for step-up application because the internal stresses set up within the transformer may damage it.

SCHEMATIC SYMBOLS FOR TRANSFORMERS

8-20. Figure 8-11 shows typical schematic symbols for transformers. View A shows the symbol for an air-core transformer. Views B and C show iron-core transformers. The bars between the windings indicate an iron core. Additional connections are frequently made to the transformer windings at points other than the ends of the windings. These additional connections are called taps. When a tap is connected to the center of the winding, it is called a center tap. View C shows the schematic representation of a center-tapped iron-core transformer.

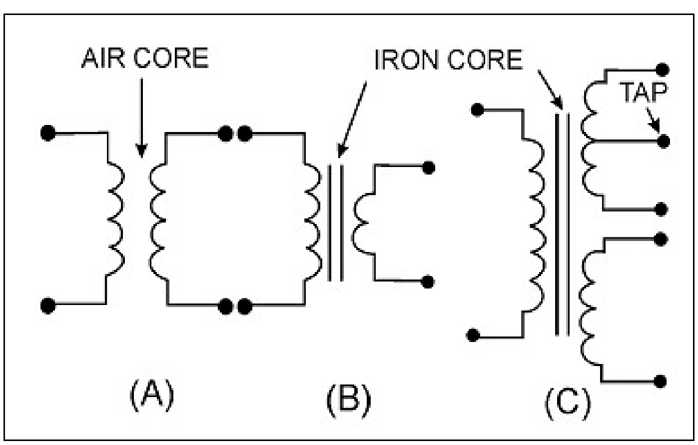

Figure 8-11. Schematic Symbols for Various Types of Transformers

NO-LOAD CONDITION

8-21. A transformer can supply voltages that are usually higher or lower than the source voltage. This is done through mutual induction. Mutual induction takes place when the changing magnetic field produced by the primary voltage cuts the secondary winding.

8-22. A no-load condition exists when a voltage is applied to the primary but no load is connected to the secondary (see Figure 8-12). There is no current flowing in the secondary winding because of the open switch. However, with the switch open and an AC voltage applied to the primary, there is a very small amount of current, called exciting current, flowing in the primary. The exciting current "excites" the winding of the primary to create a magnetic field.

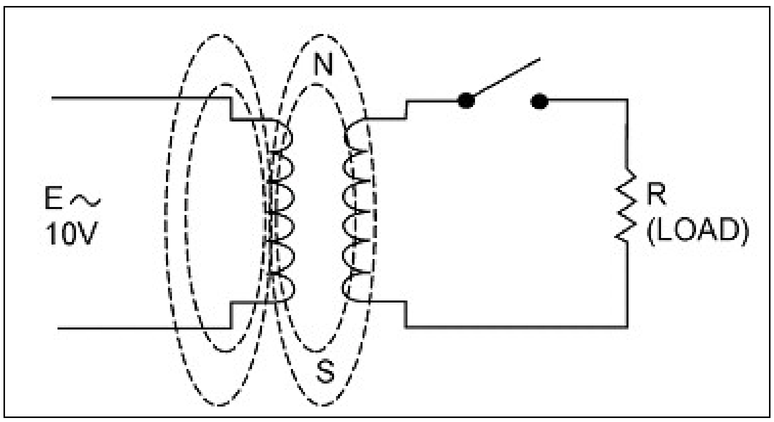

Figure 8-12. Transformer Under No-Load Conditions

8-23. The amount of the exciting current is determined by three factors (which are all controlled by transformer action):

- The amount of voltage applied.
- The resistance of the primary winding's wire and core losses.
- The inductive reactance, which depends on the frequency of the exciting current.

This very small amount of exciting current serves two functions:

- Most of the exciting energy is used to support the magnetic field of the primary.
- A small amount of energy is used to overcome the resistance of the wire and core. This energy is dissipated in the form of heat (power loss).

Exciting current will flow in the primary winding at all times to maintain this magnetic field. However, no transfer of energy will take place as long as the secondary circuit is open.

WARNING

The open secondary leads provide a potential hazard to personnel. Should a path between the secondary leads develop, current will result. The soldier should NEVER come in contact with the exposed secondary leads when the primary leads are energized.

COUNTER ELECTROMOTIVE FORCE

8-24. When an AC flows through a primary winding, a magnetic field is established around the winding. As the lines of flux expand outward, relative motion is present and a CEMF is induced in the winding. Flux leaves the primary at the north pole and enters the primary at the south pole. The CEMF induced in the primary has a polarity that opposes the applied voltage, thereby opposing the flow of current in the primary. It is the CEMF that limits the exciting current to a very low value.

VOLTAGE IN THE SECONDARY

8-25. Figure 8-12 also shows a voltage is induced into the secondary winding of a transformer. As the exciting current flows through the primary, magnetic lines of force are generated. During this time, while current is increasing in the primary, magnetic lines of force expand outward from the primary and cut the secondary. A voltage is induced into a winding when magnetic lines cut across it. Therefore, the voltage across the primary causes a voltage to be induced across the secondary.

TURNS AND VOLTAGE RATIOS

8-26. The total voltage induced into the secondary winding of a transformer is determined mainly by the ratio of the number of turns in the primary to the number of turns in the secondary and by the amount of voltage applied to the primary. Figure 8-13, view A, shows a transformer whose primary consists of 10 turns of wire and whose secondary consists of a single turn of wire. As lines of flux generated by the primary expand and collapse, they cut both the 10 turns of the primary and the single turn of the secondary. Since the length of the wire in the secondary is about the same as the length of the wire in each turn of the primary, CEMF induced into the secondary will be the same as the EMF induced into each turn in the primary. This means that if the voltage applied to the primary winding is 10 volts, then the CEMF in the primary is almost 10 volts. Therefore, each turn in the primary will have an induced CEMF of about $1/10^{th}$ of the total applied voltage, or 1 volt. Since the same flux lines cut the turns in both the secondary and the primary, each turn will have an EMF of 1 volt induced into it. The transformer in Figure 8-13, view A, has only one turn in the secondary. Therefore, the EMF across the secondary is 1 volt.

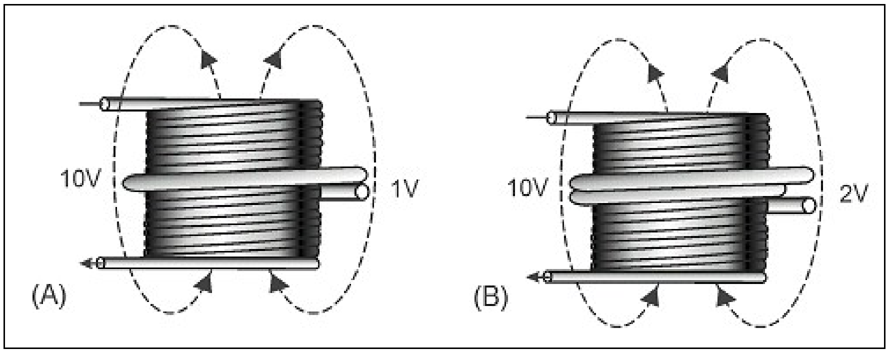

Figure 8-13. Transformer Turns and Voltage Ratios

8-27. The transformer in Figure 8-13, view B, has a 10-turn primary and a 2-turn secondary. Since the flux induces 1 volt per turn, the total voltage across the secondary is 2 volts. The volts per turn are the same for both the primary and secondary windings. Since the CEMF in the primary is equal (or almost equal) to the applied voltage, a proportion may be set up to express the value of the voltage induced in terms of the voltage applied to the primary and the number of turns in each winding. This proportion also shows the relationship between the number of turns in each winding and the voltage across each winding.

8-28. This proportion is expressed by the following equation:

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

Where:

N_p = number of turns in the primary

E_s = voltage induced in the secondary

E_p = voltage applied to the primary

N_s = number of turns in the secondary

N_p = number of turns in the primary

The equation shows that the ratio of secondary voltage to primary voltage equals the ratio of secondary turns to primary turns. The equation can be written as follows:

$$E_p \times N_s = E_s \times N_p$$

8-29. The following formulas are derived from the above equation:

Solving for E_s:

$$E_s = \frac{(E_p) \times (N_s)}{N_p}$$

Solving for E_p:

$$E_p = \frac{(E_s) \times (N_p)}{N_s}$$

If any three quantities in the above formulas are known, the fourth quantity can be calculated.

> ***Example:*** A transformer has 200 turns in the primary, 50 turns in the secondary, and 120 volts applied to the primary. Use the following equation to determine the voltage across the secondary (E_s).

Equation:

$$\mathbf{E_s = \frac{(E_p) \times (N_s)}{N_p}}$$

Given:

N_p = 200 turns

N_s = 50 turns

E_p = 120 volts

E_s = ?

Solution:

$$E_s = \frac{(E_p) \times (N_s)}{N_p}$$

$$E_s = \frac{(120 \text{ volts}) \times (50 \text{ turns})}{200 \text{ turns}}$$

$$E_s = 30 \text{ volts}$$

8-30. The transformer in the above problem has fewer turns in the secondary than the primary. As a result, there is less voltage across the secondary than across the primary. A transformer in which the voltage across the secondary is less than the voltage across the primary is called a step-down transformer. The ratio of a four-to-one step-down transformer is written 4:1. A transformer that has fewer turns in the primary than in the secondary will produce a greater voltage across the secondary than the voltage applied to the primary. A transformer in which the voltage across the secondary is greater than the voltage applied to the primary is called a step-up transformer. The ratio of a one-to-four step-up transformer is written as 1:4. In the two ratios, the value of the primary winding is always stated first.

EFFECT OF A LOAD

8-31. When an electrical load is connected across the secondary winding of a transformer, current flows through the secondary and the load. The magnetic field produced by the current in the secondary interacts with the magnetic field produced by the current in the primary. This interaction results from the mutual inductance between the primary and secondary windings.

POWER RELATIONSHIP BETWEEN PRIMARY AND SECONDARY WINDINGS

8-32. The turns ratio of a transformer affects current as well as voltage. If voltage is doubled in the secondary, current is halved in the secondary. However, if voltage is halved in the secondary, current is doubled in the secondary. In this manner, all the power delivered to the primary by the source is also delivered to the load by the secondary (minus whatever power is consumed by the transformer in the form of losses). The transformer in Figure 8-14, shows the turns ratio is 20:1. If the input to the primary is 10 amperes at 450 volts, the power in the primary is 4,500 watts (P = I x E). If the transformer has no losses, 4,500 watts is delivered to the secondary. The secondary steps down the voltage to 22.5 volts and increases the current to 200 amperes. Therefore, the power delivered to the load by the secondary is P = E x I = 22.5 volts x 200 amps = 4,500 watts.

8-33. The reason for this is that when the number of turns in the secondary is decreased, the opposition to the flow of the current is also decreased. Therefore, more current will flow in the secondary. If the turns ratio of the transformer is increased to 1:2 (step up), the number of turns on the secondary is twice the number of turns on the primary. This means the opposition to current is doubled. Therefore, voltage is doubled, but current is halved due to the increased opposition to current in the secondary. With the exception of the power consumed within the transformer, all power delivered to the primary by the source will be delivered to the load. The form of the power may change, but the power in the secondary almost always equals the power in the primary. This can be expressed in the formula:

$$P_s = P_p - P_1$$

Where:

P_s = power delivered to the load by the secondary

P_p = power delivered to the primary by the source

P_1 = power losses in the transformer

ACTUAL TRANSFORMER LOSSES

8-34. Practical power transformers, although highly efficient, are not perfect devices. Small power transformers used with electrical components have an 80 to 90 percent efficiency range. Large distribution system transformers may have efficiencies exceeding 98 percent.

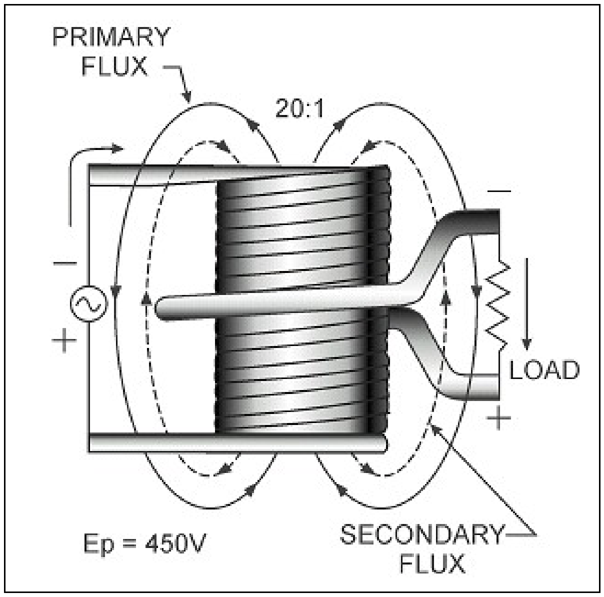

Figure 8-14. Simple Transformer Indicating Primary and Secondary Winding Flux Relationship

8-35. The total power loss in a transformer is a combination of losses. One loss is due to the resistance in the conductors of the primary and secondary windings. This loss is called copper loss or I^2R loss. As current increases through the resistance of the conductor, there is a drop in voltage proportional to the increase in current flow. This phenomenon is found wherever there is a resistance. Ohm's law shows this.

> **Example**: The initial electrical load demands 10 amperes. The resistance in the transformer winding conductor is .4 ohms. The voltage drop across the winding conductor is 4 volts.
>
> Equation:
>
> **E = I x R**
>
> Where:
>
> I = 10 amps
>
> R = .4 ohms
>
> Solution:
>
> E = I x R
>
> E = 10 amps x .4 ohms
>
> E = 4 volts

If the electrical demand in the example above is increased and a current of 70 amperes is now required, the voltage drop across the winding conductor will increase, as follows:

Equation:

$E = I \times R$

Where:

$I =$ 70 amps

$R =$ .4 ohms

Solution:

$E = I \times R$

$E =$ 70 amps x .4 ohms

$E =$ 28 volts

8-36. As current flow increases, there is a resulting increase in heat. The resistance of copper increases as current and temperature increase. This further affects the voltage drop. This makes secondary voltage decrease as load is applied.

8-37. Whenever current flows in a conductor, power is dissipated in the resistance of the conductor in the form of heat. The amount of power dissipated by the conductor is directly proportional to the resistance of the wire and to the square of the current through it.

8-38. The greater the value of the current or the resistance, the greater the power dissipated. To determine the power consumed or lost due to resistance of the conductor, use the formula **$P = I \times E$** or **$P = I^2R$**, as shown in the following example:

Equation:

$P = I \times E$ **or** $P = I^2 \times R$

Where:

$I =$ 70 amps

$R =$ .4 ohms

$E =$ 28 volts

Solution:

$P = I \times E$

$P =$ 70 amps x 28 volts

$P =$ 1,960 watts

Or:

$P = I^2 \times R$

$P =$ (70 amps)^2 x (.4 ohms)

$P =$ 4,900 amps x .4 ohms

$P =$ 1,960 watts

8-39. The resistance of a given conductor or winding is a function of the diameter of the conductor and its length. Large diameter, lower resistance wire is required for high-current-carrying applications. Small diameter, higher resistance wire can be used for low-current-carrying applications.

8-40. Two other losses are due to eddy currents and hysteresis in the core of the transformer. Copper loss, eddy current loss, and hysteresis loss result in undesirable conversion of electrical energy to heat energy.

EDDY CURRENT LOSS

8-41. The core of a transformer is usually constructed of some type of ferromagnetic material because it is a good conductor of magnetic lines of flux. Whenever the primary of an iron-core transformer is energized by an AC source, a fluctuating magnetic field is produced. This magnetic field cuts the conducting core material and induces a voltage into it. The induced voltage causes random currents to flow through the core, which dissipate power in the form of heat. These undesirable currents are eddy currents.

8-42. To reduce the loss resulting from eddy currents, transformer cores are laminated. Since the thin, insulated laminations do not provide an easy path for current, eddy current losses are greatly reduced.

HYSTERESIS LOSS

8-43. When a magnetic field is passed through a core, the core material becomes magnetized. To become magnetized, the domains within the core must align themselves with the external field. If the direction of the field is reversed, the domains must turn so that their poles are aligned with the new direction of the external field.

8-44. Transformers normally operate at 60 hertz. Each tiny atomic particle domain must realign itself twice each cycle or a total of 120 times a second. The energy used to turn each domain is dissipated as heat within the iron core. This is hysteresis loss, which results from molecular friction. Hysteresis loss can be held to a small value by proper choice of core materials during the manufacturing process.

TRANSFORMER EFFICIENCY

8-45. The input power and the output power from the transformer must be known to compute the efficiency of a transformer. The input power equals the product of the voltage applied to the primary and the current in the primary. The output power equals the product of the voltage across the secondary and the current in the secondary. The difference between the input power and the output power represents a power loss. This percentage of efficiency of a transformer is calculated using the following standard efficiency formula:

$$\text{Efficiency (in \%)} = \frac{P_{out}}{P_{in}} \times 100$$

Where:

P_{out} = total output power delivered to the load.

P_{in} = total input power.

TRANSFORMER RATINGS

8-46. When a transformer is to be used in a circuit, more than just the turns ratio must be considered. The voltage, current, and power-handling capabilities of the primary and secondary windings must also be considered.

8-47. The maximum voltage that can safely be applied to any winding is determined by the type and thickness of the insulation used. When a better (and thicker) insulation is used between the windings, a higher maximum voltage can be applied to the windings.

8-48. The maximum current that can be carried by a transformer winding is determined by the diameter of the wire used for the winding. If current is excessive in a winding, a higher than ordinary amount of power will be dissipated by the winding in the form of heat. This heat may become sufficiently high to cause the insulation around the wire to break down. If this happens, the transformer will become permanently damaged.

8-49. The power-handling capability of a transformer depends on its ability to dissipate heat. If the heat can be safely removed, the power-handling capability of the transformer can be increased. This is sometimes done by immersing the transformer in oil or by using cooling fins. The power-handling capability of distribution system transformers is measured in volt-ampere units (kVA). Smaller units generally used in resistive circuits are measured in the watt unit (kW).

DISTRIBUTION TRANSFORMERS

8-50. Step-down and isolation distribution transformers supply voltages to the various circuits in an electrical system. Distribution transformers are rated at 500 kVA or less. They are the dry type and are air-cooled and drip-proof. They can operate at 30-degree inclinations. They are designed for ambient temperature operation of 40^0C and 50^0C.

8-51. The high- and low-voltage windings in a distribution transformer can usually be distinguished by observing the diameter of the conductor. Since most transformers located on board ship are the step-down type, the low-voltage winding will have the larger diameter conductor. This is because the power is not changed. The reduction in voltage means an increase of current. Current determines the diameter of the conductor.

ISOLATION TRANSFORMERS

8-52. Isolation transformers do not change either the power level or the voltage and current levels. Instead, they provide an extra degree of protection to the distribution system for those circuits that are set aside for access by other than engineering personnel and for the circuits that are available for unspecified electrical apparatus.

8-53. Should one of these circuits have a catastrophic electrical casualty that prevents local circuit breakers and overloads from operating properly, the isolation transformer prevents a mechanical connection of the circuit with the rest of the distribution system. A catastrophic electrical problem will damage the transformer and allow time for the rest of the distribution system to react to the electrical problem. The isolation transformers effectively isolate these problem circuits from the rest of the single-phase distribution system.

TRANSFORMER TAPS

8-54. Typical transformers used for electrical components and control circuits have several primary and/or secondary windings. Figure 8-15 shows the schematic symbol for a typical multitap transformer. For any given voltage across the primary, the voltage across each of the secondary windings is determined by the number of turns in each secondary. A winding may be center-tapped like the secondary 350-volt winding in Figure 8-15. To center-tap a winding means to connect a wire to the center of the coil so that between this tap and either terminal of the winding there appears one-half of the voltage developed across the entire winding.

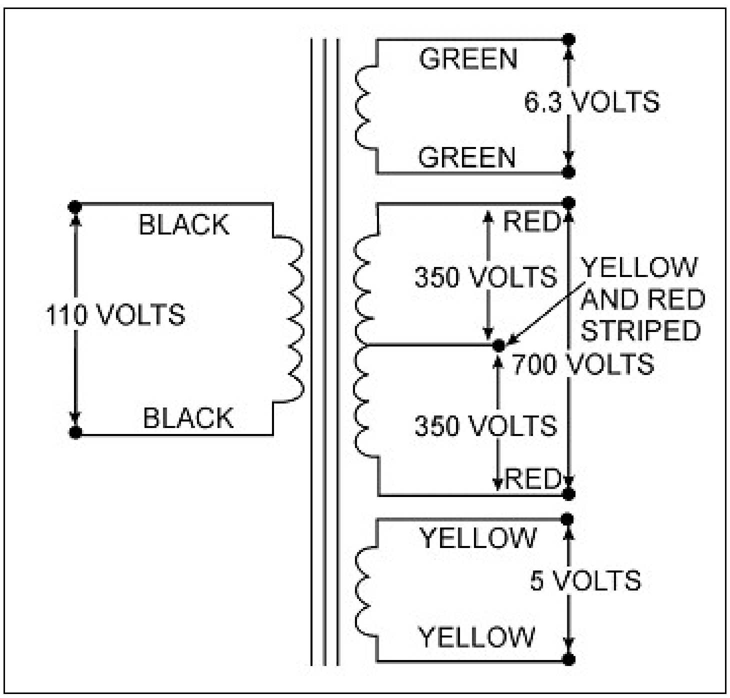

Figure 8-15. Schematic Diagram of a Typical Transformer

AUTOTRANSFORMERS

8-55. It is not always necessary to have two or more separate and distinct windings in a transformer. Figure 8-16 is a schematic diagram of an autotransformer. A single winding is tapped to produce what is electrically a primary and secondary winding.

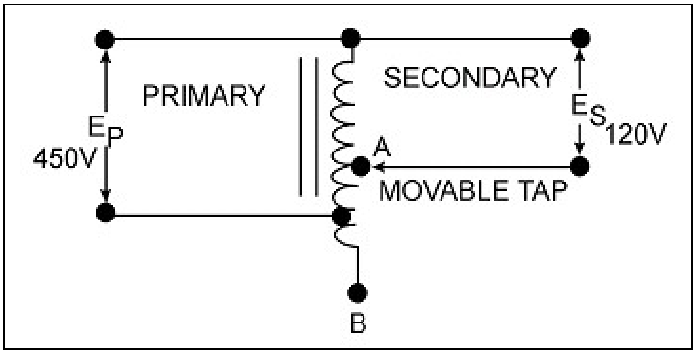

Figure 8-16. Schematic Diagram of an Autotransformer With a Movable Tap

8-56. Through inductance, the magnetic field from the power supply can produce a CEMF into the primary winding as well as an EMF into the secondary winding. Voltage is self-induced into every coil of wire.

Example: Assume that 208 volts is applied to the autotransformer in Figure 8-17. The primary includes all the turns, but the secondary includes only half the turns. The turns ratio is 2:1. Secondary voltage is as follows:

$$E_s = \frac{208 \text{ volts}}{2}$$

$$E_s = 104 \text{ volts}$$

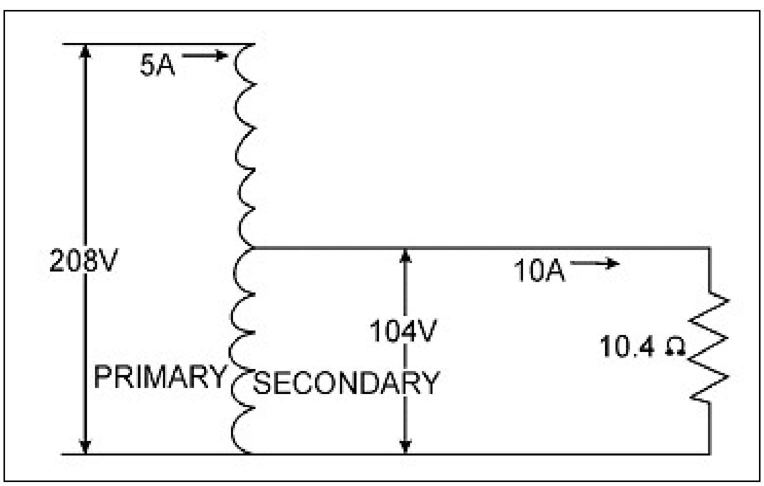

Figure 8-17. Step-Down Transformer

There is a 10.4-ohm resistive load. Load current is as follows:

$$I_s = \frac{104 \text{ volts}}{10.4 \text{ ohms}}$$

$$I_s = 10 \text{ amps}$$

Primary current is as follows:

$$I_p = \frac{10 \text{ amps}}{2}$$

$$I_p = 5 \text{ amps}$$

8-57. It may be hard at first to understand how the secondary can have twice the primary current since the primary and secondary are the same coil. However, the secondary current is the sum of two separate currents. One is the primary current, which also flows in the secondary circuit. The other is produced by the back-voltage (CEMF), which is self-induced in the secondary part of the coil. The primary current of 5 amperes is conducted to the secondary current. The other 5 amperes is transformed in the transformer.

8-58. The autotransformer is used extensively for reduced voltage starting of larger motors. This is one of the most effective ways to hold the line current and voltage to a minimum when a maximum current (or torque per line ampere) is required at the motor.

8-59. The autotransformer is also used for starting motors. It is never used to supply feeders or branch circuits in the distribution system. The schematic drawing in Figure 8-18, view A, shows a properly functioning autotransformer. Figure 8-18, view B, shows a damaged autotransformer. If this type of casualty took place, the voltage to the load would increase to the value available at the primary side. This could be electrically devastating to all the electrical loads connected to the secondary side.

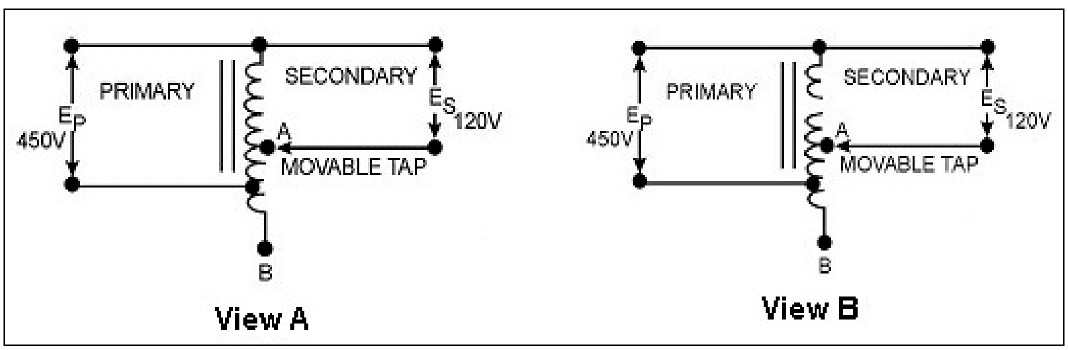

Figure 8-18. Properly Functioning and Damaged Autotransformer Winding

TRANSFORMER SAFETY

8-60. Keep in mind the following additional rules when working or inspecting transformers:

- Remove the transformer from all power sources in the primary and secondary circuitry.
- Remove all the fuses from the power source.
- Trip circuit breakers and take action to prevent their accidental resetting.
- Short out transformer secondaries before connecting and disconnecting equipment.
- To prevent potentially high voltage and current levels, always connect a load to the secondary side of the transformer before energizing the primary. The voltmeter is an excellent high-resistance load when connected with alligator clips.

TRANSFORMERS

Questions

1. A transformer is often used to do what?
2. What is one important advantage of using AC over DC?
3. The terms “step up” and “step down” refer to what?
4. For what purpose are transformers used in switchboards?
5. What are the four principle parts of a transformer?
6. What are the most commonly used core materials?
7. What are the two main shapes of cores?
8. What terms are used for testing unmarked transformers?
9. When does mutual induction take place?
10. What is the main way that the total voltage is induced into the secondary winding of a transformer?
11. What is the name given to the transformer in which the voltage across the secondary is less than the voltage across the primary?
12. What do the turns ration of a transformer affect?
13. What is the efficiency range of small power transformers used with electrical components?
14. What is the name of the loss due to the resistance in the conductors of the primary and secondary windings?
15. What are done to transformer cores to reduce the loss resulting from eddy currents?
16. What must be known to compute the efficiency of a transformer?
17. What determines the maximum voltage that can be safely applied to any winding?
18. What determines the maximum current that can be carried by a transformer winding?
19. How are distribution transformers rated?
20. For what purpose are autotransformers extensively used?

Appendix A

Check on Learning

CHAPTER 1, SAFETY

Answers

1. Current.
2. Short circuit.
3. NCOIC or OIC.
4. FM 4-25.11.
5. Alcohol, opiates, or other depressant substances.
6. Rubber mat.
7. On stomach with head turned to one side.
8. Carbon dioxide.

CHAPTER 2, FUNDAMENTALS OF ELECTRICITY

Answers

1. Anything that occupies space. Solids, liquids, gas.
2. A substance that cannot be reduced to a simpler substance by chemical means.
3. A chemical combination of elements that can be separate by chemical means but not by physical means.
4. A combination of elements and/or compounds (not chemically combined) that can be separated by physical means.
5. The smallest particle of an element that retains the characteristics of that element.
6. Numerically according to the complexity of their atoms.
7. Kinetic energy and potential energy.
8. The number and position of the electrons within the atom.
9. Valence shell.
10. Ionization.
11. Silver.
12. Semiconductors.
13. By friction.
14. Excess or lack of electrons.
15. Like charges repel each other and unlike charges attract each other.
16. The space between and around charged bodies.
17. Positive charge leaving and negative charge entering.
18. Reluctance.
19. Like poles repel and unlike poles attract.
20. The number of electrons spinning in each direction.
21. Magnetic field.

CHAPTER 2, FUNDAMENTALS OF ELECTRICITY

Answers

22. Imaginary lines used to illustrate and describe the pattern of the magnetic field.
23. From the south pole to the north pole.
24. A soft-iron case (called a magnetic screen or magnetic shield).
25. Bar, ring, and horseshoe.
26. The ability to do work.
27. Potential energy.
28. Difference of potential.
29. The electron flow is directly proportional to the applied voltage.
30. A device that can supply and maintain voltage while an electrical apparatus is connected to its terminals.
31. Six.
32. The difference in temperature between the hot and cold junctions.
33. Various compounds of silver oxide or copper oxide.
34. Wet cell and dry cell.
35. To produce vast quantities of electric power from mechanical devices.
36. Conductor.
37. The velocity of the existing moving electrons.
38. Amperes.
39. The physical structure of a material.
40. Temperature coefficient.
41. Mho.
42. Carbon resistors.
43. Freed and variable.
44. Potentiometer and the rheostat.
45. Four.
46. Resistors.

CHAPTER 3, DIRECT CURRENT

Answers

1. A drawing of a circuit that uses symbols to represent the various circuit components.
2. The third quantity.
3. The rate at which work is done.
4. The watt.
5. Voltage (E), current (I), resistance (R), and power (P).
6. The rate at which the device converts electrical energy into another form of energy (such as light, heat, or motion).
7. When resistors with wattage ratings greater than 5 watts are needed.
8. Power conversion.
9. A series circuit.
10. The source voltage.
11. The applied voltage.
12. Whether the values are component values or total values.
13. A break interrupts a complete conducting pathway.
14. An accidental path of low resistance that passes an abnormal high amount of current.
15. Internal resistance.
16. Maximum power.
17. One.
18. Single.
19. A connecting point for two resistors.
20. Total voltage and total current.
21. Reciprocal method.
22. Reduction to an equivalent circuit.
23. Equivalent circuits.

CHAPTER 4, BATTERIES

Answers

1. A device that transforms chemical energy into electrical energy.
2. Two electrodes and a container that holds the electrolyte.
3. They are the conductors by which the current leaves or returns to the electrolyte.
4. A path for electron flow.
5. Primary and secondary.
6. By forcing an electric current through it in the direction opposite to that of discharge.
7. The conversion of the cell's chemical energy to a productive electrical energy.
8. They are attracted to the negative charge on the carbon electrode.
9. Yes.
10. Polarization.
11. By removing and controlling impurities in the cells.
12. Dry cell.
13. In a cylindrical zinc container.
14. In a cool place (refrigerated spaces).
15. Lead-acid, nickel-cadmium, silver-zinc, and silver-cadmium.
16. Lead-acid cell.
17. Nickel-cadmium cell.
18. Silver-zinc cell.
19. High cost and low voltage production.
20. In series or in parallel.
21. 1.5 volts.
22. In parallel.
23. By their size and markings.
24. A nameplate giving the type description and electrical characteristics.
25. Leak test.
26. 18 degrees Fahrenheit.
27. Negative.
28. The amount of active ingredients in the electrolyte of a battery and the specific gravity of the electrolyte.
29. 30 (.030).
30. Oxidation.
31. 2.33.
32. Flush the area with large quantities of fresh water for a minimum of 15 minutes.
33. Ampere-hours.
34. Initial, normal, equalizing, floating, and fast.

CHAPTER 5, CONCEPTS OF ALTERNATING CURRENT

Answers

1. Current that changes constantly in amplitude and which reverses direction at regular intervals.
2. Transformer.
3. Sine wave.
4. Magnetic force.
5. An arrow (see Figure 5-3, view A).
6. The direction of current in that wire.
7. Hysteresis loss.
8. Electromagnetic induction.
9. Left-hand rule.
10. One cycle per second.
11. The number of complete cycles of AC or voltage completed each second.
12. The distance from zero to the maximum value of each alternation.
13. The distance along the wave from one point to the same point on the next cycle.
14. Maximum or peak, peak-to-peak, effective, instantaneous, or average.
15. Power formula.
16. When they go through their maximum and minimum points at the same time and in the same direction.
17. Any device that consumes all power in the form of heat and/or light.
18. Effective.

CHAPTER 6, INDUCTANCE

Answers

1. The characteristic of an electrical circuit that opposes the starting, stopping, or changing of current flow.
2. Henry (H).
3. The characteristic of mass that opposes a change in velocity.
4. Whenever there is relative motion between a magnetic field and a conductor.
5. It becomes negatively charged.
6. Counter electromotive force (CEMF).
7. A conductor, a magnetic field, and relative motion.
8. The induced EMF in any circuit is always in a direction that opposes the effect that produced it.
9. According to core type.
10. The number of turns, the coil diameter, the length of the coil conductor, the type of core material, and the number of layers of winding in the coil.
11. It increases.
12. When they are wound into coils.
13. By multiplying the square of current in the inductor by the resistance of the winding (I^2R).
14. By mounting the coils on a common core.

CHAPTER 7, CAPACITANCE

Answers

1. Electrostatic lines of force.
2. Positive to negative.
3. Store energy.
4. Dielectric.
5. The electrons in the dielectric are attracted to the top plate while being repelled from the bottom plate.
6. Farads.
7. The area of the plates, the distance between the plates, and the dielectric constant of the insulating material between the plates.
8. The dielectric will break down and arcing will occur between the capacitor plates.
9. With another capacitor equal to but not greater than 20 percent of the original microfarad rating.
10. With another capacitor within plus or minus 10 percent of the original microfarad rating.
11. Dielectric hysteresis and dielectric leakage.
12. Displacement current.
13. In series or in parallel.
14. According to the type of material used as its dielectric (such as paper, oil, mica, or electrolyte).
15. Oil capacitor.
16. When the values are changing together through a cycle so that the values begin, peak, and change direction together.
17. 360 degrees.
18. In ohms.
19. Zero point.
20. The combining of resistance and reactance to oppose the flow of current.

CHAPTER 8, TRANSFORMERS

Answers

1. Step up or step down voltage.
2. The voltage and current levels can be increased or decreased by means of a transformer.
3. Actions of the voltage.
4. Step down the voltage for indicating lights.
5. The core, the primary winding, the secondary winding, and the enclosure.
6. Air, soft iron, and steel.
7. Hollow core and shell core.
8. Additive polarity and subtractive polarity.
9. When the changing magnetic field produced by the primary voltage cuts the secondary winding.
10. By the ratio of the number of turns in the primary to the number of turns in the secondary and by the amount of voltage applied to the primary.
11. Step-down transformer.
12. Current as well as voltage.
13. 80 to 90 percent.
14. Copper loss or I^2R loss.
15. They are laminated.
16. Input power and the output power.
17. The type and thickness of the insulation used.
18. The diameter of the wire used for the winding.
19. 500 kVA or less.
20. Reduced voltage starting of larger motors.

Glossary

AC. Alternating current.

Air-core transformer. A transformer composed of two or more coils that are wound around a nonmetallic core.

Alternating current. An electrical current that constantly changes amplitude and changes in polarity at regular intervals.

Ammeter. An instrument for measuring the amount of electron flow in amperes.

Ampere. The basic unit of electrical current.

Anode. A positive electrode of an electromagnetic device (such as a primary or secondary electric cell) toward which the negative ions are drawn.

Apparent power. That power apparently available for use in an AC circuit containing a reactive element. It is the product of effective voltage times effective current expressed in volt-amperes. It must be multiplied by the power factor to obtain the true power available.

Attraction. The force that tends to make two objects approach each other. Attraction exists between two unlike magnetic poles (north and south) or between two unlike static charges (plus and minus).

ATTN. Attention.

Average value of AC. The average of all the instantaneous values of one-half cycle of alternating current.

Battery. A device for converting chemical energy into electrical energy.

Battery capacity. The amount of energy available from a battery. Battery capacity is expressed in ampere-hours.

BDU. Battle dress uniform.

Branch. An individual current path in a parallel circuit.

C. Carbon.

Capacitance. The property of an electrical circuit that opposes changes in voltage.

Capacitive reactance. The opposition offered to the flow of alternating current by capacitance, expressed in ohms. The symbol for capacitive reactance is Xc.

Capacitor. An electrical device capable of storing electrical energy in an electrostatic field.

Cathode. The general name for any negative electrode.

Cell. A single unit that transforms chemical energy into electrical energy. Batteries are made up of cells.

CEMF (counter electromotive force). An electromotive force (voltage) induced in a coil that opposes applied voltage; voltage induced in the coils of a load.

Charge. Represents electrical energy. A material having an excess of electrons is said to have a negative charge. A material having an absence of electrons is said to have a positive charge.

Charge cycle. The period of time that a capacitor in an electrical circuit is storing a charge.

Circuit. The complete path of an electric current.

Circular mil. An area equal to that of a circle with a diameter of 0.001 inch. It is used for measuring the cross-sectional area of wires.

Coil. An inductive device created by looping turns of wire around a core.

Combination circuit. A series-parallel circuit.

Conductance. The ability of a material to conduct or carry an electric current. It is the reciprocal of resistance of the material and is expressed in mhos or siemens.

Conductivity. The ease with which a substance transmits electricity.

Conductor. A material with a large number of free electrons; a material that permits electric current to flow.

Copper loss (I^2R loss). The power lost due to the resistance of the conductors. In transformers, the power is lost because of current flow (I) through the resistance (R) of the windings.

Core. Any material that affords a path for magnetic flux lines in a coil.

Coulomb. A measure of the quantity of electricity. One coulomb equals 6.242 x 1,018 electrons.

Coulomb's law. Also called the law of electric charges or the law of electrostatic attraction. Coulomb's law states that charged bodies attract or repel each other with a force that is directly proportional to the product of their individual charges and inversely proportional to the square of the distance between them.

Coupling, coefficient of. An expression of the extent to which two inductors are coupled by magnetic lines of force. This is expressed as a decimal or percentage of maximum possible coupling and represented by the letter K.

CPR. Cardiopulmonary resuscitation.

Cross-sectional area. The area of a slice of an object. When applied to electrical conductors, it is usually expressed in circular mils.

Current. The drift of electrons past a reference point; the passage of electrons through a conductor. It is measured in amperes.

Cycle. One complete positive and one complete negative alternation of a current or voltage.

D.C. District of Columbia.

DA. Department of the Army.

DC. Direct current.

Dead short. A short circuit having minimum resistance.

Dielectric. An insulator; the insulating material between the plates of a capacitor.

Dielectric constant. The ratio of capacitance of a capacitor with a dielectric between the electrodes to the capacitance of a capacitor with air between the electrodes.

Dielectric field. The space between and around charged bodies in which their influence is felt; also called electric field of force or electrostatic field.

Dielectric hysteresis loss. Power loss of a capacitor due to the changes in orientation of electron orbits in the dielectric caused by rapid reversal in polarity of line voltage. The higher the frequency, the greater the loss.

Dielectric leakage. Power loss of a capacitor due to leakage of current through the dielectric. It also relates to leakage resistance. The higher the leakage resistance, the lower the dielectric leakage.

Direct current. An electric current that flows in one direction.

Displacement current. The current that appears to flow through a capacitor.

Domain theory. A theory of magnetism based upon the electron-spin principle. Spinning electrons have a magnetic field. If more electrons spin in one direction than another, the atom is magnetized.

Dry cell. An electric cell in which the electrolyte is not a liquid. In most dry cells, the electrolyte is in paste form.

E. Voltage.

Eddy current. Induced circulating currents in a conducting material that are caused by a varying magnetic field.

Eddy current loss. Losses caused by random current flowing in the core of a transformer. Power is lost in the form of heat.

EFF. Efficiency.

Effective value. Same as root mean square.

Efficiency. The ratio of output power to the input power; generally expressed as a percentage.

Electrical charge. Symbol Q, q. Electric energy stored on or in an object. The negative charge is caused by an excess of electrons; the positive charge is caused by a deficiency of electrons.

Electric current. Electric energy stored on or in an object. It is the negative charge caused by an excess of electrons or the positive charge caused by a deficiency of electrons. Its symbol is Q, q.

Electrochemical. The action of converting chemical energy into electrical energy.

Electrode. The terminal at which electricity passes from one medium into another, such as in an electrical cell where the current leaves or returns to the electrolyte.

Electrolyte. A solution of a substance that is capable of conducting electricity; may be either a liquid or a paste.

Electromagnet. An electrically excited magnet capable of exerting mechanical force or performing mechanical work.

Electromagnetic. Describes the relationship between electricity and magnetism; having both magnetic and electrical properties.

Electromagnetic induction. The production of a voltage in a coil due to a change in the number of magnetic lines of force (flux linkages) passing through the coil.

Electromagnetism. The generation of a magnetic field around a current-carrying conductor.

Electron. The elementary negative charge that revolves around the nucleus of an atom.

Electron shell. A group of electrons that have a common energy level that forms part of the outer structure (shell) of an atom.

Electrostatic. Pertaining to electricity at rest, such as charges on an object (static electricity).

Electrostatic field. The field of influence between two charged bodies.

Element. A substance in chemistry that cannot be divided into simpler substances by any means normally available.

Electromotive force (EMF). The force that causes electricity to flow between two points with different electrical charges; or when there is a difference in potential between the two points, the unit of measurement in volts.

EMF. Electromotive force.

Energy. The ability or capacity to do work.

Equivalent resistance. A resistance that represents the total ohmic values of a circuit component or group of circuit components. It is usually drawn as a single resistor when simplifying complex circuits.

Exciting current. The current that flows in the primary winding of a transformer, which produces a magnetic flux field. Also called magnetizing current.

Farad. The basic unit of capacitance. A capacitor has a capacitance of 1 farad when a voltage change of 1 volt per second across it produces a current of 1 ampere.

Ferromagnetic material. A highly magnetic material (such as iron, cobalt, nickel, or alloys).

Field of force. Describes the total force exerted by an action-at-a-distance phenomenon, such as gravity upon matter, electric charges acting upon electric charges, and magnetic forces acting on other magnets or magnetic materials.

Fixed resistor. A resistor having a definite resistance value that cannot be adjusted.

Flux. In electrical or electromagnetic devices, a general term used to designate collectively all the electric or magnetic lines of force in a region.

Flux density. The number of magnetic lines of force passing through a given area.

Frequency (f). The number of complete cycles per second existing in any form of wave motion, (such as the number of cycles per second of an alternating current).

G. Conductance.

Gas. One of the four states of matter, characterized by having no fixed shape or volume. For example, steam is a gas.

Gaseous. Having the form of or being of gas; having no fixed shape or volume.

Graph. A pictorial presentation of the relationship between two or more variable quantities, (such as between applied voltage and the current it produces in a circuit).

Ground potential. Zero potential with respect to the ground or earth.

H. Henry.

H_2SO_4. Sulfuric acid solution (electrolyte).

Henry (H). The electromagnetic unit of inductance or mutual inductance. The inductance of a circuit is 1 henry when a current variation of 1 ampere per second induces 1 volt. It is the basic unit of inductance. In radio, smaller units are used, such the millihenry (mH), which is one-thousandth of a henry (H), and the microhenry (uH), which is one-millionth of a henry.

Hertz (Hz). A unit of frequency equal to one cycle per second.

Horsepower. The English unit of power, equal to work done at a rate of 550 foot-pounds per second, equal to 746 watts of electrical power.

Horseshoe magnet. A permanent magnet bent into the shape of a horseshoe or having a U-shape to bring the two poles near each other.

HP. Horsepower.

HQ. Headquarters.

Hydrometer. An instrument used to measure specific gravity. In batteries, hydrometers are used to indicate the state of charges by the specific gravity of the electrolyte.

Hysteresis. The time lag of the magnetic flux in a magnetic material behind the magnetizing force producing it; caused by the molecular friction of the molecules trying to align themselves with the magnetic force applied to the material.

Hysteresis loss. The power loss in an iron-core transformer or other alternating-current device as a result of magnetic hysteresis.

I. Current.

Impedance. The total opposition offered to the flow of an alternating current. It may consist of any combination of resistance, inductive reactance, and capacitive reactance. The symbol for impedance is Z.

Induced charge. An electrostatic charge produced on an object by the electric field that surrounds a nearby object.

Induced current. Current that flows in a conductor because of a changing magnetic field.

Induced electromotive force. The electromotive force induced in a conductor due to the relative motion between a conductor and a magnetic field.

Induced voltage. See *induced electromotive force*.

Inductance. The property of a circuit that tends to oppose a change in the existing current flow. The symbol for inductance is L.

Induction. The act or process of producing voltage by the relative motion of a magnetic field across a conductor.

Inductive coupling. Coupling of two coils by means of magnetic lines of force. In transformers, it is coupling applied through magnetic lines of force between the primary and secondary windings.

Inductive reactance. The opposition to the flow of an alternating current caused by the inductance of a circuit, expressed in ohms. It is identified by the letter X.

In phase. Applied to the condition that exists when two waves of the same frequency pass through their maximum and minimum values of like polarity at the same instant.

Infinite. Extending indefinitely, endless; boundless having no limits; an incalculable number.

Instantaneous value. The magnitude at any particular instant when a value is continually varying with respect to time.

Insulation. A material used to prevent the leakage of electricity from a conductor and to provide mechanical spacing or support to protect against accidental contact; a material in which current flow is negligible, used to surround or separate a conductor to prevent loss of current.

Inversely. Inverted or reversed in position or relationship.

Ion. An electrically charged atom or group of atoms. Negative ions have an excess of electrons; positive ions have a deficiency of electrons.

Ionize. To make an atom or molecule of an element lose an electron, as by X-ray bombardment, and therefore be converted into a positive ion. The freed electron may attach itself to a neutral atom or molecule to form a negative ion.

Junction. The connection between two or more conductors; the contact between two dissimilar metals or materials, as in a thermocouple.

Kilo. A prefix meaning one thousand.

Kinetic energy. Energy that a body possesses by virtue of its motion.

Kirchhoff's laws. The algebraic sum of the currents flowing toward any point in an electrical network is zero; the algebraic sum of the products of the current and resistance in each of the conductors at any closed path in a network equals the algebraic sum of the electromotive forces in the path.

kV. Kilovolt.

kWh. Kilowatt hour.

Lag. The amount one wave is behind another in time, expressed in electrical degrees.

Laminated core. A core built up from thin sheds of metal insulated from each other and used in transformers.

Law of magnetism. Like poles repel; unlike poles attract.

Lead. The opposite of lag; also a wire or connection.

Lead-acid battery. A cell in an ordinary storage battery, in which electrodes are grids of lead containing an active material consisting of certain lead oxides that change composition during charging and discharging. The electrodes are plates that are immersed in an electrolyte of diluted sulfuric acid.

Leakage flux. Magnetic lines of flux produced by the primary winding that do not link the turns of the secondary winding.

Leakage resistance. The electrical resistance that opposes the flow of current through the dielectric of a capacitor. The higher the leakage resistance, the slower the capacitor will discharge or leak across the dielectric.

Left-hand rule for generators. A rule or procedure used to determine the direction of current flow in a generator.

Lenz's law. The current induced in a circuit due to its motion in a magnetic field or to a change in its magnetic flux in such a direction as to exert a mechanical force opposing the motion or to oppose the change in flux.

Lines of force. A line in an electric or magnetic field that shows the direction of the force.

Liquid. One of the four states of matter, characterized by having a definite volume but no definite form. For example, water is a liquid.

Load. A device through which an electric current flows and that changes electrical energy into another form; power consumed by a device or circuit in performing its function.

Local action. A continuation of current flow within an electrical cell when there is no external load. It is caused by impurities in the electrode.

μA. Microampere.

M. The symbol for mutual inductance.

mA. Milliampere.

Magnetic field. Region in which the magnetic forces created by a permanent magnet or by a current-carrying conductor or coil can be detected.

Magnetic lines of force. Imaginary lines used for convenience to designate the direction in which magnetic forces are acting as a result of magneto-motive force.

Magnetic poles. The section of a magnet where the flux lines are concentrated; also where the flux lines enter and leave the magnet.

Magnetism. The property possessed by certain materials by which these materials can exert mechanical force on neighboring masses of magnetic materials and can cause currents to be induced in conducting bodies moving relative to the magnetized bodies.

Matter. Any physical entity that possesses mass.

Mega. A prefix meaning one million.

Mho. Unit of conductance; the reciprocal of the ohm. See *Siemens*.

Micro. A prefix meaning one-millionth.

μV. Microvolt.

Milli. A prefix meaning one-thousandth.

MOS. Military occupational specialty.

Mutual flux. The total flux in the core of a transformer that is common to both the primary and the secondary windings. The flux links both windings.

Mutual inductance. A circuit property existing when the relative position of two inductors causes the magnetic lines of force from one to link with the turns of another. The symbol for mutual inductance is M.

mV. Millovolt.

NBC. nuclear, biological, chemical.

NCOIC. Noncommissioned officer in charge.

Negative alternation. The negative half of an AC waveform.

Negative temperature coefficient. The temperature coefficient expressing the amount of reduction in the value of a quantity (such as resistance for each degree of increase in temperature).

Network. A combination of electrical components. In a parallel circuit, it is composed of two or more branches.

Neutral. In a normal condition (neither negative or positive). A neutral object has a normal number of electrons.

NICAD. Nickel-cadmium.

No. Number.

No-load condition. The condition that exists when an electrical source or the secondary of a transformer is operated without an electrical load.

Ω. Greek letter omega.

OIC. Officer in charge.

Ohm. The unit of electrical resistance. It is that value of electrical resistance through which a constant potential difference of 1 volt across the resistance will maintain a current flow of 1 ampere through the resistance.

Ohm's law. The current in an electrical circuit is directly proportional to the electromotive force in the circuit. The most common form of the law is E = IR, where E is the electromotive force or voltage across the circuit, I is the current flowing in the circuit, and R is the resistance in the circuit.

Open circuit. The condition of an electrical circuit caused by the breaking of continuity of one or more of the conductors of the circuit, usually an undesired condition; a circuit that does not provide a complete path of current flow.

P. Power.

Parallel circuit. Two or more electrical devices connected to the same pair of terminals so separate current flows through each. Electrons have more than one path to travel from the negative to the positive terminal.

Peak to peak. The measure of absolute magnitude of an AC waveform, measured from the greatest positive alternation to the greatest negative alternation.

Peak value. The highest value, either positive or negative, in an alternating current system.

Period. The time required to complete one cycle of a waveform.

Permeability. The measure of the ability of a material to act as a path for magnetic lines of force.

Phase. The angular relationship between two alternating currents or voltages when the voltage or current is plotted as a function of time. When the two are in phase, the angle is zero and both reach their peak simultaneously. When out of phase, one will lead or lag the other. At the instant when one is at its peak; the other will not be at peak value and (depending on the phase angle) may differ in polarity as well as magnitude.

Phase angle. The number of electrical degrees of lead or lag between the voltage and current waveforms in an AC circuit.

Phase difference. The time in electrical degrees by which one wave leads or lags another.

Photoelectric voltage. A voltage produced by light.

Piezoelectric effect. The effect of producing a voltage by placing stress, either by compression, expansion, or twisting, on a crystal and, conversely, producing a stress on a crystal by applying a voltage to it.

Plate. One of the electrodes in a storage battery.

Polarity. The condition in an electrical circuit by which the direction of the current flow can be determined, usually applied to batteries and other direct current voltage sources; two opposite charges, one positive and one negative; a quality of having two opposite poles, one north and one south.

Polarization. The effect of hydrogen surrounding the anode of a cell that increases the internal resistance of the cell; the magnetic orientation of molecules in a magnetizable material in a magnetic field, whereby tiny internal magnets tend to line up in the field.

Positive alternation. The positive half of an AC waveform.

Potential energy. Energy due to the position of one body with respect to another body or to the relative parts of the same body.

Potentiometer. A three-terminal resistor with one or more sliding contacts that functions as an adjustable voltage divider.

Power. The rate of doing work or the rate of expending energy. The unit of electrical power is the watt.

Power factor. The ratio of the actual power of an alternating or pulsating current, as measured by a wattmeter, to the apparent power, as indicated by ammeter and voltmeter readings. The power factor of an inductor, capacitor, or insulator is an expression of their losses.

Power loss. The electrical power supplied to the circuit that does no work, usually dissipated as heat.

Primary cell. An electrochemical cell in which the chemical action eats away one of the electrodes, usually the negative electrode.

Primary windings. The winding of a transformer connected to the power source.

R. Resistance.

Radio frequency (RF). Any frequency of electrical energy capable of propagation into space.

Ratio. The value obtained by dividing one number by another, indicating their relative proportions.

RC constant. Time constant of a resistor-capacitor circuit; equal in seconds to the resistance value in ohms multiplied by the capacitance value in farads.

Reactance. The opposition offered to the flow of an alternating current by the inductance, capacitance, or both in any circuit.

Reciprocal. The value obtained by dividing the number 1 by any quantity.

Reference point. A point in a circuit to which all other points in the circuit are compared.

Reluctance. A measure of the opposition that a material offers to magnetic lines of force.

Repulsion. The mechanical force tending to separate bales having like electrical charges or like magnetic polarity.

Req. Equivalent resistance.

Residual magnetism. Magnetism remaining in a substance after removal of the magnetizing force.

Resistance. The property of a conductor that determines the amount of current that will flow as the result of the application of a given electromotive force. All conductors possess some resistance, but when a device is made especially for the purpose of limiting current flow, it is called a resistor. A resistance of 1 ohm will allow current of 1 ampere to flow through it when a potential of 1 volt is applied. It is the opposition that a device or material offers to the flow of current. The effect of resistance is to raise the temperature of the material or device carrying the current. Resistance also refers to a circuit element designed to offer predetermined resistance to current flow.

Resistor. The electrical component that offers resistance to current flow. It may be a coil of fine wire or a composition rod.

Retentivity. The ability of a material to retain its magnetism.

Rheostat. A resistor whose value can be varied; a variable resistor that is used for the purpose of adjusting the current in a circuit.

RLC circuit. An electrical circuit that has the properties of resistance, inductance, and capacitance.

Root mean square (RMS). The equivalent heating value of an alternating current or voltage, as compared to a direct current or voltage. It is 0.707 times the peak value of the same sine wave.

Schematic circuit diagram. A diagram using symbols to indicate devices in a circuit. Schematics show function, not location.

Schematic symbols. A letter, abbreviation, or design used to represent specific characteristics or components on a schematic diagram.

Secondary. The output coil of a transformer.

Secondary cell. A cell that can be recharged by passing a current through the cell in a direction opposite to the discharge current.

Self-induction. The production of a counter electromotive force in a conductor when its own magnetic field collapses or expands with a change in current in the conductor.

Series circuit. An arrangement where electrical devices are connected so that the total current must flow through all the devices. Electrons have one path to travel from the negative to the positive terminal.

Series-parallel circuit. A circuit that consists of both series and parallel networks.

Shelf life. The period of time that a cell or battery may be stored and still be useful.

Shielding. A metallic covering used to prevent magnetic or electromagnetic fields from affecting an object.

Short circuit. A low-resistance connection between two points of different potential in a circuit, usually accidental and usually resulting in excessive current flow that may cause damage.

Siemens. The new and preferred term for conductance, replacing the mho.

Sine wave. The curve traced by the projection on a uniform time scale of the end of a rotating arm or vector. It is also known as a sinusoidal wave.

Solid. One of the four states of matter, characterized by having a definite volume and shape. For example, ice is a solid.

Source voltage. The device that furnishes the electrical energy used by a load.

Specific gravity. The ratio between the density of a substance and that of pure water at a given temperature.

Static electricity. Stationary electricity that is in the form of a charge. It is the accumulated charge on an object.

Switch. A device to connect, disconnect, or change the connections in an electrical circuit.

t. Time.

Tapped resistor. A wire-wound fixed resistor having one or more additional terminals along its length, generally for voltage divider applications.

TC. Training circular.

Temperature coefficient. The amount of change of resistance in a material per unit change in temperature.

Terminal. An electrical connection.

Thermocouple. A junction of two dissimilar metals that produces a voltage when heated.

Theta. The Greek letter (θ) used to represent phase angle.

Time constant. The time required to charge a capacitor to 63.2 percent of maximum voltage or discharge to 36.8 percent of its final voltage. It is the time required for the current in an inductor to increase to 63.2 percent of maximum current or decrease to 36.8 percent of its final current.

TM. Technical manual.

Tolerance. The maximum error or variation from the standard permissible in a measuring instrument; a maximum electrical or mechanical variation from specifications that can be tolerated without impairing the operation of the device.

Total resistance (R_T). The equivalent resistance of an entire circuit. For a series circuit $R_T = R_1 + R_2 + R_3 + ...R_n$. For parallel circuits:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \frac{1}{R_n}$$

Transformer. A device composed of two or more coils, linked by magnetic lines of force, used to transfer energy from one circuit to another.

Transformer efficiency. The ratio of output power to input power, generally expressed as a percentage:

Transformer, step-down. A transformer so constructed that the number of turns in the secondary winding is less than the number of turns in the primary winding. This construction will provide less voltage in the secondary circuit than in the primary circuit.

Transformer, step-up. A transformer so constructed that the number of turns in the secondary winding is more than the number in the primary winding. This construction will provide more voltage in the secondary winding than in the primary winding.

True power. The power dissipated in the resistance of the circuit or the power actually used by the circuit.

Turn. One complete loop of a conductor about a core.

Turns ratio. The ratio of number of turns in the primary winding to the number of turns in the secondary winding of a transformer.

Unidirectional. In one direction only.

Universal time constant. A chart used to find the time constant of a circuit if the impressed voltage and the values of R and C or R and L are known.

USACASCOM&FL. United States Army Combined Arms Support Command and Fort Lee.

USATRADOC. United States Army Training and Doctrine Command.

VA. Volts times amps.

Valence. The measure of the extent to which an atom is able to combine directly with other atoms. It is believed to depend on the number and arrangement of the electrons in the outermost shell of the atom.

Valence shells. The electrons that form the outermost shell of an atom.

VAR. Abbreviation for volt-amperes reactive.

Variable resistor. A wire-wound or composition resistor, the value of which may be changed.

Vector. A line used to represent both direction and magnitude; the angular difference in the direction the conductors, which are moving in relation to the magnetic lines of flux.

Volt. The unit of electromotive force or electrical pressure; 1 volt is the pressure required to send 1 ampere of current through a resistance of 1 ohm.

Voltage. Signifies electrical pressure. Voltage is a force that causes current to flow through an electrical conductor. The voltage of a circuit is the greatest effective difference of potential between any two conductors in the circuit.

Voltage divider. A series circuit in which desired portions of the source voltage may be tapped off for use in equipment.

Voltage drop. The difference in voltage between two points. It is the result of the loss of electrical pressure as current flows through a resistance.

Watt. The practical unit of electrical power. It is the amount of power used when 1 ampere of direct current flows through a resistance of 1 ohm.

Wattage rating. A rating expressing the maximum power that a device can safely handle.

Watt-hour. A practical unit of electrical energy equal to one watt of power for one hour.

Waveform. The shape of the wave obtained when instantaneous values of an alternating current quantity are plotted against time in a rectangular coordinate.

Wavelength. The distance, usually expressed in meters, traveled by a wave during the time interval of one complete cycle. It equals the velocity of light divided by the frequency.

Weber's theory. A theory of magnetism that assumes that all-magnetic material is composed of many tiny magnets. A piece of magnetic material that is magnetized has all of the tiny magnets aligned so that the north pole of each magnet points in one direction.

Wire. A solid or stranded group of solid cylindrical conductors having a low resistance to current flow, with any associated insulation.

Work. The product of force and motion.

Working voltage. The maximum voltage that a capacitor may operate at without the risk of damage.

Zn. Zinc.

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